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Anticipating Cycle 24 Minimum and Its Consequences: An Update

Robert M. Wilson and David H. Hathaway
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October 2008

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National Aeronautics and
Space Administration

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LIST OF ACRONYMS

deg	degrees of latitude
12-mma	12-mo moving average
NOAA	National Oceanic and Atmospheric Administration
SOON	Solar Optical Observing Network
USAF	United States Air Force
Y	yes

NOMENCLATURE

a	y-intercept in the inferred regression equation
A	corrected sunspot area, in millionths of the Sun's hemisphere
ad	mean or average deviation
Am	minimum value of sunspot area
AM	maximum value of sunspot area
$<A(0)>$	mean sunspot area at $t = 0$ ($E(Rm)$)
ASC	ascent duration in months
b	slope in the inferred regression equation
cl	confidence level
$D(GH)$	dominance of high-latitude spot groups
E	epoch of occurrence
$E(Am)$	epoch of sunspot area minimum value
$E(AM)$	epoch of sunspot area maximum value
$E(Gm)$	epoch of minimum number of spot groups
$E(GM)$	epoch of maximum number of spot groups
$E(Hm)$	epoch of minimum highest latitude spot group
$E(HM)$	epoch of maximum highest latitude spot group
$E(Lm)$	epoch of minimum of weighted mean latitude of all spot groups
$E(LM)$	epoch of maximum of weighted mean latitude of all spot groups
$E(Rm)$	epoch of minimum sunspot number
$E(RM)$	epoch of maximum sunspot number
$E(SM)$	epoch of maximum number of spotless days
G	number of spot groups
$G(H)$	number of high-latitude spot groups
Gm	minimum number of spot groups
GM	maximum number of spot groups

NOMENCLATURE (Continued)

$<G(0)>$	mean number of spot groups at $t = 0$ ($E(Rm)$)
H	highest-latitude spot group, in degrees
Hm	minimum value of highest-latitude spot group
HM	maximum value of highest-latitude spot group
$<H(0)>$	mean value of highest-latitude spot group at $t = 0$ ($E(Rm)$)
L	weighted mean latitude of all spot groups, in degrees
Lm	minimum value of weighted mean latitude of all spot groups
LM	maximum value of weighted mean latitude of all spot groups
$<L(0)>$	mean value of weighted mean latitude of all spot groups at $t = 0$ ($E(Rm)$)
m	minimum
M	maximum
n	sunspot cycle number
P	probability
PER	period (length or duration) in months
r	coefficient of correlation
r^2	coefficient of determination
R	sunspot number
Rm	minimum value of sunspot number (minimum amplitude)
$<Rm>$	mean value of minimum value of sunspot number
RM	maximum value of sunspot number (maximum amplitude)
$<RM>$	mean value of maximum value of sunspot number
$<R(0)>$	mean value of sunspot number at $t = 0$ ($E(Rm)$)
$\sum d^2$	sum of the square of the deviations
S	number of spotless days
sd	standard deviation
se	standard error of estimate
SM	maximum value of number of spotless days

NOMENCLATURE (Continued)

$<S(0)>$	mean value of the number of spotless days at $t = 0$ ($E(Rm)$)
t	elapsed time in months
$t(Am)$	elapsed time in months of Am relative to Rm
$t(AM)$	elapsed time in months of AM relative to Rm
$t(D(GH))$	elapsed time in months of $D(GH)$ relative to Rm
$t(Gm)$	elapsed time in months of Gm relative to Rm
$t(GM)$	elapsed time in months of GM relative to Rm
$t(Hm)$	elapsed time in months of Hm relative to Rm
$t(HM)$	elapsed time in months of HM relative to Rm
$t(Lm)$	elapsed time in months of Lm relative to Rm
$t(LM)$	elapsed time in months of LM relative to Rm
$t(SM)$	elapsed time in months of SM relative to Rm
$T(AM)$	elapsed time in months of AM relative to RM
$T(GM)$	elapsed time in months of GM relative to RM
$T(Hm)$	elapsed time in months of Hm relative to RM
$T(HM)$	elapsed time in months of HM relative to RM
$T(Lm)$	elapsed time in months of Lm relative to RM
$T(LM)$	elapsed time in months of LM relative to RM
$T(SM)$	elapsed time in months of SM relative to RM

TECHNICAL PUBLICATION

ANTICIPATING CYCLE 24 MINIMUM AND ITS CONSEQUENCES: AN UPDATE

1. INTRODUCTION

Several months ago, it was reported[1] that cycle 23 very probably would be a longer than average period cycle, having a period either falling within the "period gap" (127–134 mo), where no previous cycles have ever had a period length, or more likely, a period equal to or longer than 135 mo. July 2007 marked the 135th month for cycle 23 from May 1996 (minimum smoothed monthly mean sunspot number occurrence date), having a 12-mo moving average (12-mma) of monthly mean sunspot number (*R*) equal to 7.0, a value slightly higher than both the long-term mean (6.1) and the median (5.3) based on cycles 12–23. Through December 2007, *R* further decreased to 5.0 and the length of cycle 23 is now known to span at least 140 mo. On the basis of the most reliably known sunspot cycles (12–22), longer period cycles, including cycles 12–14 and 20, have periods ranging between 135 and 142 mo, averaging about 139 mo. Hence, the 90-percent prediction interval for modern era longer period cycles is about 139.0 ± 6.9 mo, inferring only a 5-percent chance that cycle 24's sunspot minimum amplitude (*Rm*) will occur later than about July 2008.

Since the earlier report,[1] high-latitude (≥25 deg) new-cycle spots, indicative of cycle 24 (negative leading polarity in the Sun's northern hemisphere), have now been reported (in January, April, and May 2008), which is a precondition for the imminent onset of cycle minimum.[2,3] Because high-latitude new-cycle spots have now appeared, both the 12-mma values of weighted mean latitude (*L*, weighted by sunspot area) and highest latitude spots (*H*) have shifted slightly upward, thereby yielding tentative minima for both parameters, which is also a precondition for the imminent onset of cycle minimum. While true, the ratio of monthly number of high-latitude groups to total number of groups has not yet equaled or exceeded 0.50, a condition sometimes used by researchers to establish the epoch of sunspot cycle minimum,[4] since old and new sunspot cycles typically overlap by about 1–3 years.[5]

Likewise, the number of spotless days (*S*) has continued to increase with the passage of time, another precondition for the imminent onset of cycle minimum.[2,4,6,7] The first spotless day during the decline of cycle 23 was reported in January 2004, the first occurrence of 10 or more spotless days was reported in February 2006 and the first occurrence of 20 or more spotless days was reported in April 2007. Through December 2007, the 12-mma of S measures 18.1, the highest 12-mma value since cycle 19 (21.4 in April 1954). Between January 2004 and December 2007, there have been 239 spotless days, and through June 2008 there have been 357 spotless days. Previously, it was reported[1] that the number of spotless days for cycle 24 should measure less than 560 between the first and last spotless day occurrences, with that length being less than 62 mo, inferring only a 5-percent chance that a spotless day would be expected after about March 2009 (based on extrapolation of the inferred fit to cycle 24), with the last spotless day occurring at least 10 mo after sunspot minimum. So, if March 2008 happens to be the true sunspot minimum date for cycle 24, as presumed by the National Oceanic and Atmospheric Administration (NOAA) Solar Cycle Prediction Panel,[8] then the last spotless day would be expected after January 2009. Sunspot maximum amplitude would be expected to follow the last spotless day occurrence by 20–42 mo (the 90-percent prediction interval based on extrapolation of the inferred fit to cycle 24).[1]

This Technical Publication examines a number of additional solar-cycle related parameters and their epochs of occurrence based on their 12-mma values relative to sunspot minimum and maximum. The correlative behavior of sunspot minimum and maximum amplitudes (Rm and RM, respectively) between minimum and maximum values of the solar-cycle related parameters are examined, and the 2007 12-mma values are compared to superposed epochs of the solar-cycle related parameters (using sunspot minimum occurrence as the defining epoch of superposition) to estimate the nearness of cycle minimum. Additionally, the occurrences of high-latitude spots and the actual dates of high-latitude spot dominance are determined relative to sunspot cycle minimum, and the behavior of R in the vicinity of sunspot cycle minimum, in particular, when R is approximately below 15. Lastly, the possible consequences regarding the occurrence of sunspot minimum for cycle 24, its size, and the size and occurrence of its sunspot maximum are noted.

2. RESULTS AND DISCUSSION

2.1 Minimum and Maximum Parametric Values and Their Timing Signatures

Table 1 gives the minimum (*m*) and maximum (*M*) 12-mma values for selected solar-cycle related parameters and their epochs of occurrence (*E*) for cycles 12–23, the most reliably known sunspot cycles. The parameters include *R*, number of groups (*G*), corrected sunspot area (*A*) in millionths of the solar hemisphere, weighted mean latitude (*L*) of the sunspot groups, the highest observed latitude for spot groups (*H*), and the number of spotless days (*S*). The 12-mma values of *R* were obtained from the Solar Influences Data Analysis Center of the Royal Observatory of Belgium[9] (also available through NOAA).[10] Likewise, the 12-mma values of *S* were computed from the daily record of *R* from the aforementioned Web sites. The 12-mma values for *G*, *A*, *L*, and *H* were computed from records maintained at NASA/Marshall Space Flight Center,[11] based on photographic records obtained by the Royal Greenwich Observatory (1874–1976) and visual records obtained by the United States Air Force (USAF)/NOAA Solar Optical Observing Network (SOON) system (since 1976). To compensate for the change from the Royal Greenwich Observatory to the USAF/NOAA SOON system, sunspot areas have been increased by a factor of 1.4 times (see also Wilson and Hathaway).[12,13] Associated with each of the parametric minimum and maximum values is the respective epoch of occurrence date when the parametric value occurred. Below each parametric value are the median, mean, standard deviation (*sd*), mean or average deviation (*ad*), and range (low and high observed values). Values in parentheses for cycle 24 are tentative values based on known values through December 2007, which could slightly change with the passage of time.

Figure 1 displays the cyclic variation of the minimum values given in table 1, plotted as the thin jagged line in each subpanel. The thin horizontal line in each subpanel is the median and the thick heavy line is the two-cycle moving average (to demonstrate trending). Based on the two-cycle moving average, minimum values of *R*, *G*, and *A* increased in value over time between cycles 14 and 21, but now appear to be decreasing. Because of the inverse relationship between values of *R*, *G*, and *A* as compared to *S*, maximum values for *S* decreased in value over time between cycles 14 and 21, but now appear to be increasing. Based on two-cycle moving averages of *L*, its minimum values increased in value between cycles 13 and 19, but now appear to be decreasing. For *H*, however, there has been a general increase with time between cycles 13 and 22, although smaller values will prevail in cycles 23 and 24 (perhaps, even beyond). The circled points plotted for cycle 24 are the tentative values identified in table 1. The circled values for *R*, *G*, *A*, and *S* for cycle 24 are the December 2007 values, which will be replaced as future values become known (12-mmas always run 6 mo behind calendar time) if they are smaller (larger in the case for *S*) in value. The circled values for *L* and *H*, however, correspond to values from earlier dates (respectively, May and June 2007) and these may very well be the actual minimum values associated with cycle 24. (The 12-mma values of *L* and *H* continue to increase since May/June 2007.)

Figure 2 displays the cyclic variation of the maximum values of *R*, *G*, *A*, *L*, and *H* given in table 1, plotted similarly to figure 1 (this same pattern of presentation will be used in succeeding

Table 1. Minimum and maximum values of selected solar-cycle related parameters and their epochs of occurrence based on 12-mo moving averages.

Cycle	*Rm*	*E(Rm)*	*Gm*	*E(Gm)*	*Am**	*E(Am)*	*Lm*	*E(Lm)*	*Hm*	*E(Hm)*	*SM*	*E(SM)*	*RM*	*E(RM)*	*GM*	*E(GM)*	*AM**	*E(AM)*	*LM*	*E(LM)*	*HM*	*E(HM)*
12	2.2	12-1878	0.15	12-1878	15.1	12-1878	7.3	09-1878	7.8	09-1878	25.0	10-1878	74.6	12-1883	6.29	03-1884	1,406.6	11-1883	21.8	02-1880	31.5	11-1880
13	5.0	03-1890	0.48	10-1889	56.5	02-1890	6.6	02-1888	12.6	05-1888	17.9	02-1890	87.9	01-1894	8.66	09-1893	1,610.6	01-1894	24.0	07-1890	32.8	04-1892
14	2.6	01-1902	0.20	01-1902	26.3	05-1901	5.7	11-1900	8.6	11-1900	24.3	01-1902	64.2	02-1906	5.74	02-1906	1,192.3	06-1905	20.9	11-1902	32.2	03-1905
15	1.5	08-1913	0.15	08-1913	6.9	08-1913	6.1	06-1912	9.9	06-1912	26.2	08-1913	105.4	08-1917	9.58	07-1917	1,570.9	08-1917	23.2	04-1914	40.5	10-1915
16	5.6	08-1923	0.63	08-1923	49.8	08-1923	7.6	10-1921	18.5	07-1921	17.8	10-1923	78.1	04-1928	7.07	04-1928#	1,475.3	04-1926	24.4	05-1924	34.8	10-1924
17	3.4	09-1933	0.41	09-1933	27.7	09-1933	8.0	07-1933	12.5	02-1933	20.8	09-1933	119.2	04-1937	10.69	04-1937	2,160.1	05-1937	24.0	09-1935	36.5	01-1938
18	7.7	02-1944	0.74	02-1944	101.8	04-1944	8.0	11-1942	16.8	10-1942	14.9	02-1944	151.8	05-1947	11.85	11-1947	2,713.5	05-1947	22.7	11-1945	40.5	02-1947
19	3.4	04-1954	0.36	04-1954	23.5	04-1954	7.5	10-1952	15.2	06-1953	21.4	04-1954	201.3	03-1958	14.82	03-1958	3,547.7	11-1957	26.9	02-1955	43.6	01-1957
20	9.6	10-1964	1.05	06-1964	51.9	10-1964	8.9	05-1962	17.9	03-1963	9.8	12-1964	110.6	11-1968	9.33	06-1970	1,619.3	04-1968	22.3	01-1966	38.3	04-1967
21	12.2	06-1976	1.09	03-1976	138.2	11-1976	8.4	11-1975	19.4	01-1975	9.7	09-1975	164.5	12-1979	14.88	06-1979	2,526.4	01-1982	21.7	07-1977	40.5	07-1978
22	12.3	09-1986	1.00	03-1986	88.9	09-1986	6.5	03-1986	21.5	09-1984	11.7	03-1986	158.5	07-1989	13.57	02-1991	2,592.7	05-1989	25.2	10-1987	42.4	05-1990
23	8.0	05-1996	0.81	08-1996	70.3	05-1996	7.8	12-1995	16.1	10-1995	13.6	07-1996	120.8	04-2000	10.23	12-2001	2,048.8	02-2002	23.1	02-1998	38.4	12-1999
24	(5.0)	(12-2007)	(0.53)	(12-2007)	(61.7)	(12-2007)	(6.6)	(05-2007)	(11.7)	(06-2007)	(18.1)	(12-2007)	–	–	–	–	–	–	–	–	–	–
All Cycles: 12-23																						
med.	5.3		0.56		50.9		7.55		15.7		17.85		114.9		9.91		1834.1		23.15		38.35	
mean	6.1		0.59		54.7		7.4		14.7		17.8		119.7		10.23		2038.7		23.4		37.7	
sd	3.8		0.35		39.3		1.0		4.4		5.9		41.9		3.10		694.4		1.7		4.1	
low	1.5		0.15		6.9		5.7		7.8		9.7		64.2		5.74		1192.3		20.9		31.5	
high	12.3		1.09		138.2		8.9		21.5		26.2		201.3		14.88		3547.7		26.9		43.6	
ad	3.2		0.30		30.3		0.8		3.7		4.8		33.0		2.45		559.5		1.3		3.4	

*Area is increased by 40% after the end of 1976 to compensate for change in areal determination methodology. Prior to January 1977, area was determined photographically by the Royal Greenwich Observatory. From January 1977, area is determined visually using the USAF/NOAA SOON system. Median, mean, *sd*, low, high, and *ad* excludes cycle 24 potential values. Values for cycle 24 are tentative. # means same value was recorded in 06–1928. Area is corrected in millionths of a solar hemisphere.

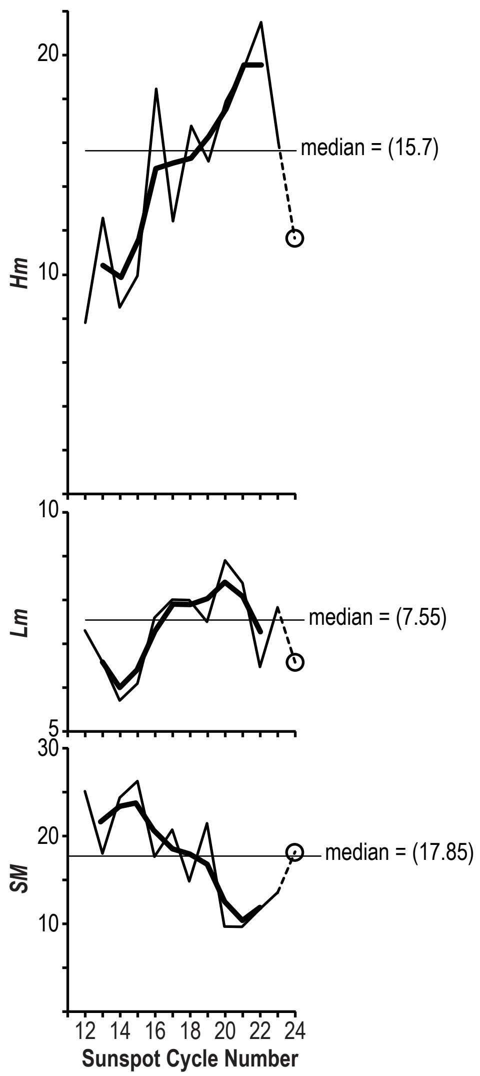

Figure 1. Cyclic variation of *Rm*, *Gm*, *Am*, *SM*, *Lm*, and *Hm* for cycles 12–24. Circled values represent tentative values for cycle 24, which may change for *Rm*, *Gm*, *Am*, and *SM*, but are considered valid for *Lm* and *Hm*.

figures, as well). Again, there is an upward movement in the parametric maximum values over time from cycles 13/14 through cycle 19 (through cycle 21 for maximum number of spot groups (*GM*)), which now appear destined to smaller values in the coming solar cycles (at least near-term).

Based on their two-cycle moving averages, as shown in figures 1 and 2, cycles 13–17 have parametric values that are much less robust as compared to those for more recent cycles 18–22, with parametric behaviors being quite similar to each other. Hence, cycles 13–17 typically have minimum and maximum values (*R*, *G*, *A*, *L*, and *H*) below their median values (maximum number of spotless days (*SM*) values above its median), while cycles 18–22 have minimum and maximum values above their median values (*SM* below its median). The trending after cycle 22 appears to be reversing (downward for *R*, *G*, *A*, *L*, and *H*, and upward for *S*).

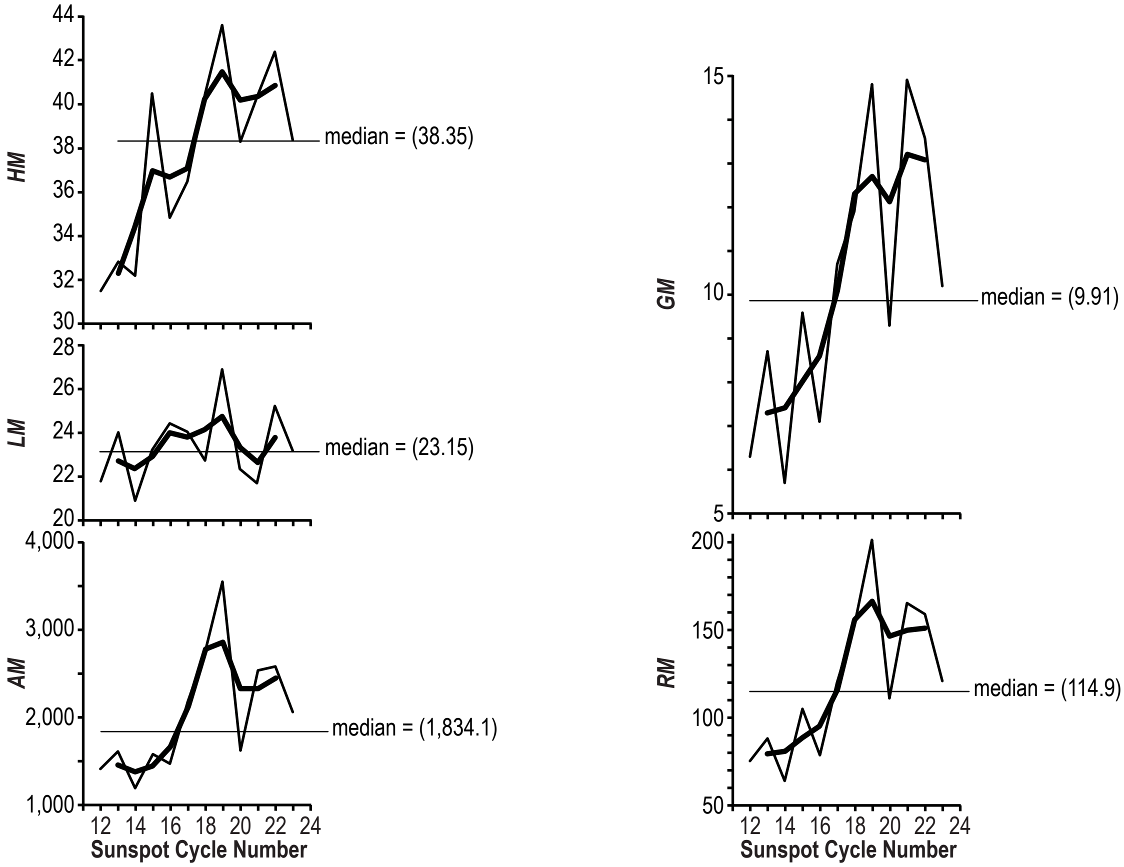

Figure 2. Cyclic variation of *RM*, *GM*, *AM*, *LM*, and *HM* for cycles 12–23.

Figure 3 shows the cyclic variation of the elapsed time in months (*t*) from the epoch of sunspot minimum (*E*(*Rm*)) for each of the parameters minimum number of spot groups (*Gm*), minimum value of sunspot area (*Am*), *SM*, minimum value of weighted mean latitude of all spot groups (*Lm*) and minimum value of highest-latitude spot group (*Hm*). For *t*(*Gm*), it usually occurs simultaneously with *Rm* (cycles 12 and 14–19). For cycles 13 and 20–22, *t*(*Gm*) occurred prior to *Rm* (leading by 2–6 mo). For cycle 23, its *t*(*Gm*) lagged *Rm* by 3 mo. For *t*(*Am*), it too usually occurs simultaneously with *Rm* (cycles 12, 15–17, 19–20 and 22–23). For cycles 13–14, *t*(*Am*) led *Rm* by 1 and 8 mo, respectively. For cycles 18 and 21, *t*(*Am*) lagged *Rm* by 2 and 5 mo, respectively. For *t*(*SM*), it also usually occurs simultaneously with *Rm* (cycles 14–15 and 17–19). For cycles 12–13 and 21–22, *t*(*SM*) preceded *Rm* by 2, 1, 9, and 6 mo, respectively, while for cycles 16, 20, and 23, *t*(*SM*) followed *Rm* by 2 mo. For *t*(*Lm*), its median is –14 mo and its range is –29 to –2 mo, meaning that *Lm* has always led *Rm*. The same is true for *t*(*Hm*), having a median of –15 mo and range of –25 to –3 mo.

Figure 4 shows the cyclic variation of *t* from the epoch of sunspot minimum (*E*(*Rm*)) for each of the parameters *RM*, *GM*, *AM*, *LM*, and *HM*. The plot of *t*(*RM*) is really a plot of the cyclic variation of ascent (*ASC*) duration (the elapsed time from *E*(*Rm*) to *E*(*RM*)). For cycles 12–23, the median is 47 mo and the range is 34 to 60 mo. The appearance of a possible four-cycle saw-tooth pattern in the two-cycle moving averages is intriguing, especially, if it repeats a third time. Presuming that it will repeat, one infers that the two-cycle moving average for *t*(*RM*) will move upward

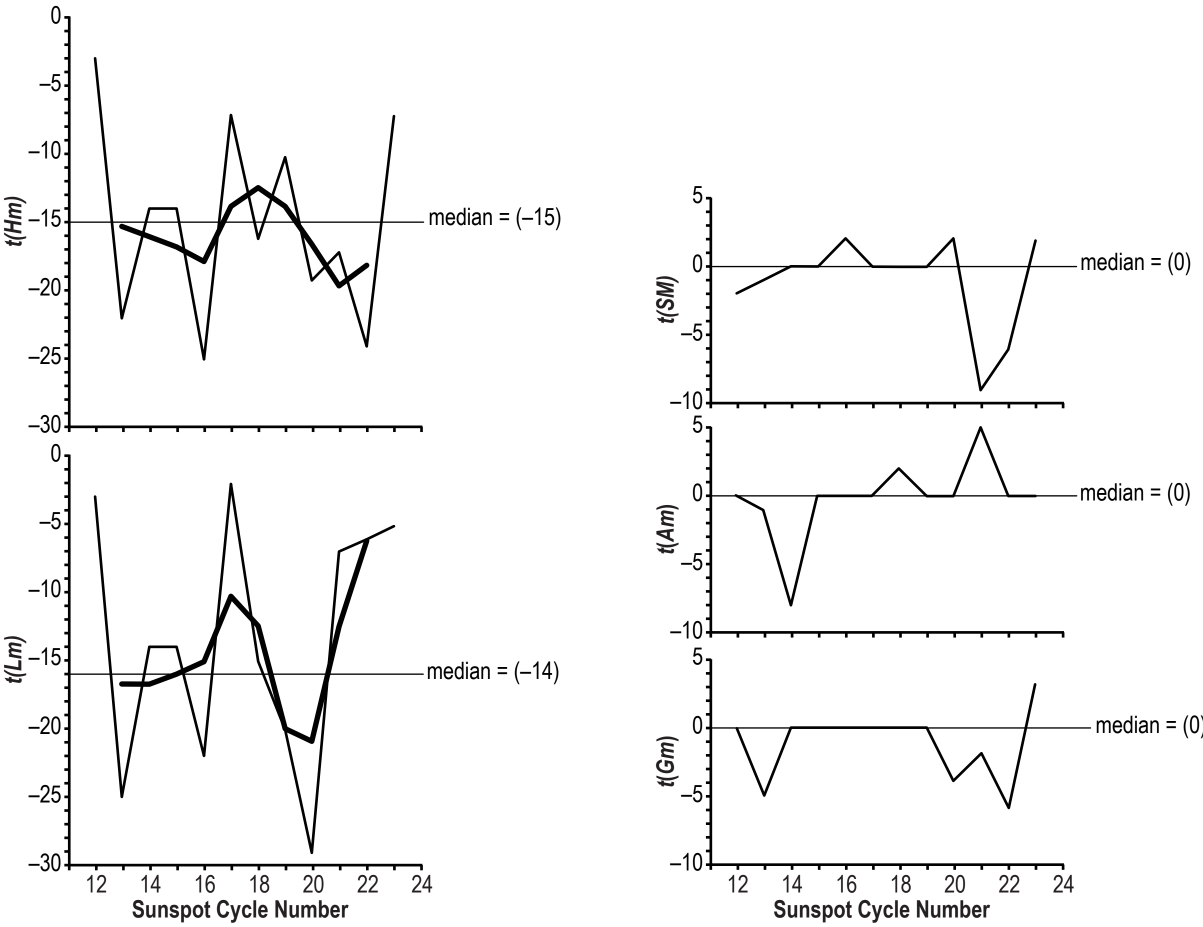

Figure 3. Cyclic variation of elapsed time in months of parametric minimum values relative to *E*(*Rm*) for cycles 12–23.

(from 39 mo) for cycles 23 and 24. (An ascent of about 44 ± 5 mo has been forecast[14,15] for cycle 24, based on precursor information regarding the expected size of cycle 24 and use of the Waldmeier effect,[16-19] the inverse relationship between *RM* and A*SC*.)

For *t*(*GM*), the median is 48 mo and range is 36 to 68 mo; for *t*(*AM*), the median is 43.5 mo and range of 32 to 69 mo; *t*(*LM*) has a median of 13 mo and range of 9 to 24 mo; and *t*(HM) has a median of 31.5 mo and range of 14 to 52 mos. Thus, *LM* has always preceded *RM* and, except for cycles 17 and 22, *HM* has always preceded *RM*. It is interesting to note that local peaks in the two-cycle moving average of *t*(*HM*) correspond with local dips in the two-cycle moving average of *t*(*RM*), while local dips in *t*(*HM*) correspond to local peaks in *t*(*RM*).

Table 2 summarizes the parametric epochal lead/lag time in months relative to *E*(*Rm*) discussed above and visualized in figures 3 and 4. The statistics associated with each parameter are given at the bottom (as in table 1).

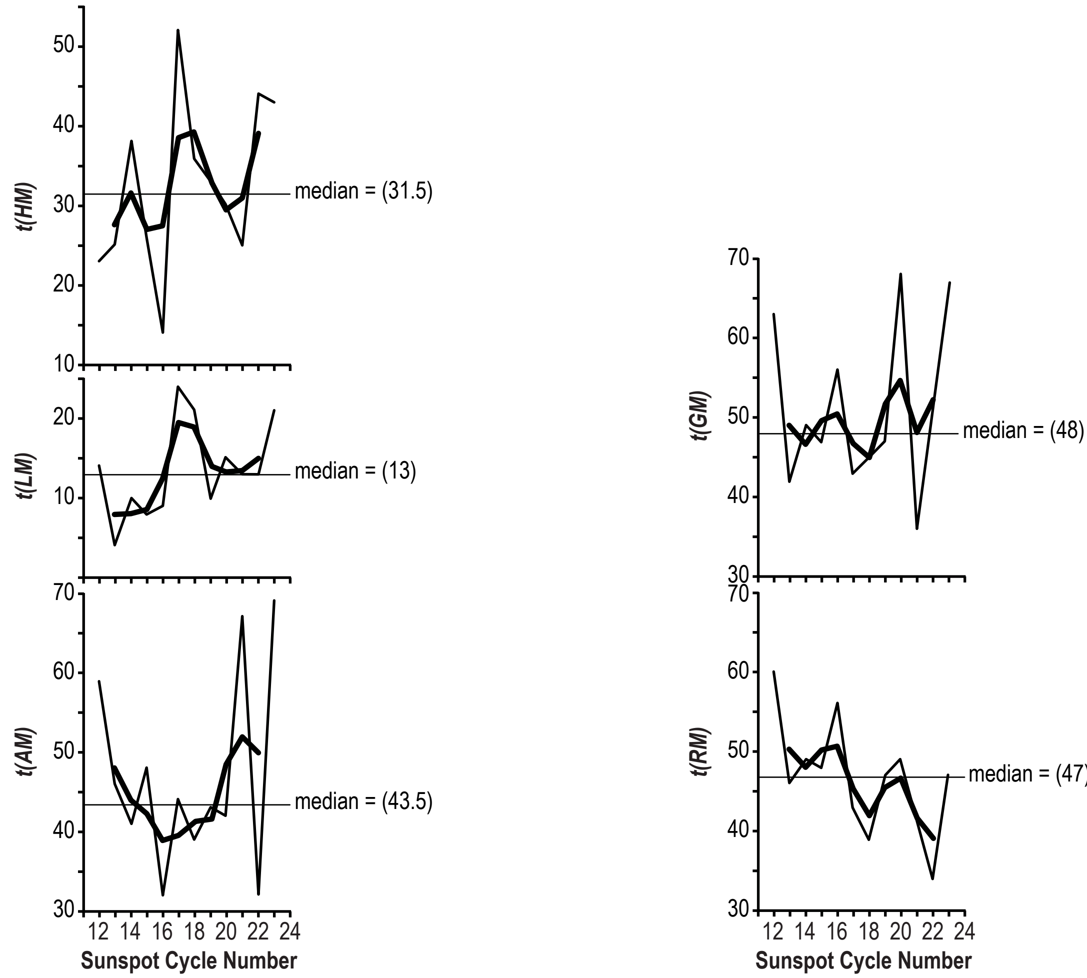

Figure 4. Cyclic variation of elapsed time in months of parametric maximum values relative to $E(Rm)$ for cycles 12–23.

Figure 5 displays the cyclic variation of the elapsed time (T) in months from the epoch of sunspot maximum ($E(RM)$) for each of the parameters GM, AM, SM, LM, and HM. For $T(GM)$, while its median is 0 and its range is –6 to 20 mo, the two-cycle moving average has crept later in time from 3 mo before RM to 13 mo after RM. Cycles 20, 22, and 23 have $T(GM)$ of about 20 mo after RM, being associated with secondary bursts of solar activity. For $T(AM)$, while its median is about 0 (–0.5) and its range is –24 to 25 mo, the two-cycle moving average has also crept later in time from about 12 mo before RM (cycle 16) to about 11 mo after RM (cycle 22). Cycles 21 and 23 both have $T(AM)$ of about 24 mo after RM, being associated with secondary bursts of solar activity. For $T(SM)$, the median is –47 mo (being associated with the occurrence of sunspot minimum) and the range is –62 (cycle 12) to –40 mo (cycle 22). For $T(LM)$, while the median is –35.5 mo and the range is –47 to –18 mo, the two-cycle moving average has decreased from about 42 mo prior to RM (cycle 13) to about 24 mo prior to RM (cycles 18 and 22). For $T(HM)$, while the median is –15.5 mo and the range is –42 to 10 mo, the two-cycle moving average has decreased from about 25 mo prior to RM (cycles 15/16) to about 0 (cycle 23), having a behavior similar to that for $T(LM)$, with cycles 17 and 22 having $T(HM)$ of about 10 mo.

Table 2. Parametric epochal lead/lag times relative to $E(Rm)$.

Cycle	t(Gm)	t(Am)	t(Lm)	t(Hm)	t(GM)	t(AM)	t(LM)	t(HM)	t(SM)
12	0	0	–3	–3	63	59	14	23	–2
13	–5	–1	–25	–22	42	46	4	25	–1
14	0	–8	–14	–14	49	41	10	38	0
15	0	0	–14	–14	47	48	8	26	0
16	0	0	–22	–25	56	32	9	14	2
17	0	0	–2	–7	43	44	24	52	0
18	0	2	–15	–16	45	39	21	36	0
19	0	0	–18	–10	47	43	10	33	0
20	–4	0	–29	–19	68	42	15	30	2
21	–3	5	–7	–17	36	67	13	25	–9
22	–6	0	–6	–24	53	32	13	44	–6
23	3	0	–5	–7	67	69	21	43	2
All Cycles: 12-23									
med.	0	0	–14	–15	48.0	43.5	13	31.5	0
mean	–1.3	–0.2	–13.3	–14.8	51.3	46.8	13.5	32.4	–1.0
sd	2.6	2.9	8.9	7.1	10.3	12.2	6.0	10.7	3.3
low	–6	–8	–29	–25	36	32	4	14	–9
high	3	5	–2	–3	68	69	24	52	2
ad	2.2	1.5	7.7	5.7	8.4	9.3	4.6	8.6	2.3

Note: Negative values mean parametric epoch leads $E(Rm)$. Positive values mean parametric epoch lags $E(Rm)$.

Table 3 summarizes the parametric epochal lead/lag time in months relative to $E(RM)$ discussed above and visualized in figure 5. The statistics associated with each parameter are given at the bottom. In order to be complete, $T(Lm)$ and $T(Hm)$ are also given in table 3, although they have not been depicted visually since they always occur prior to $E(Rm)$.

Figure 6 displays the cyclic variation of the elapsed time in months from parametric minimum value to maximum value (essentially, parametric ascent duration or rise time) for G, A, L, and H (Rm to RM was previously plotted in figure 4). For $t(Gm–GM)$, the median is 48 mo and the range is 39 (cycle 21) to 72 mo (cycle 20). For $t(Am–AM)$, the median is 45.5 mo and the range is 32 (cycles 16 and 22) to 69 mo (cycle 23). For $T(Lm–LM)$, the median is 26 mo and the range is 17 (cycle 12) to 44 mo (cycle 20), with a fairly steady lengthening of its parametric rise time through cycle 20. For $t(Hm–HM)$, the median is 48 mo and the range is 26 (cycle 12) to 68 mo (cycle 22), with longer parametric rise times for cycles 14, 17/18, and 22/23.

Figure 7 depicts the cyclic variation of the elapsed time in months from parametric maximum value to succeeding cycle parametric minimum value (essentially, parametric descent duration or fall time) for R, G, A, L, and H. For $t(RM–Rm)$, the median is 82 mo and the range is 65 (cycle 16) to 96 mo (cycle 13). Through December 2007, cycle 23's fall time based on R is at least 93 mo, having already exceeded that of cycles 14 and 20, with only cycle 13's fall time being longer. For $t(GM–Gm)$, the median is 75 mo and the range is 66 (cycle 22) to 100 mo (cycle 13). Through December 2007, cycle 23's fall time, based on G, is at least 73 mo. For $t(AM–Am)$, the median is 83 mo and the range

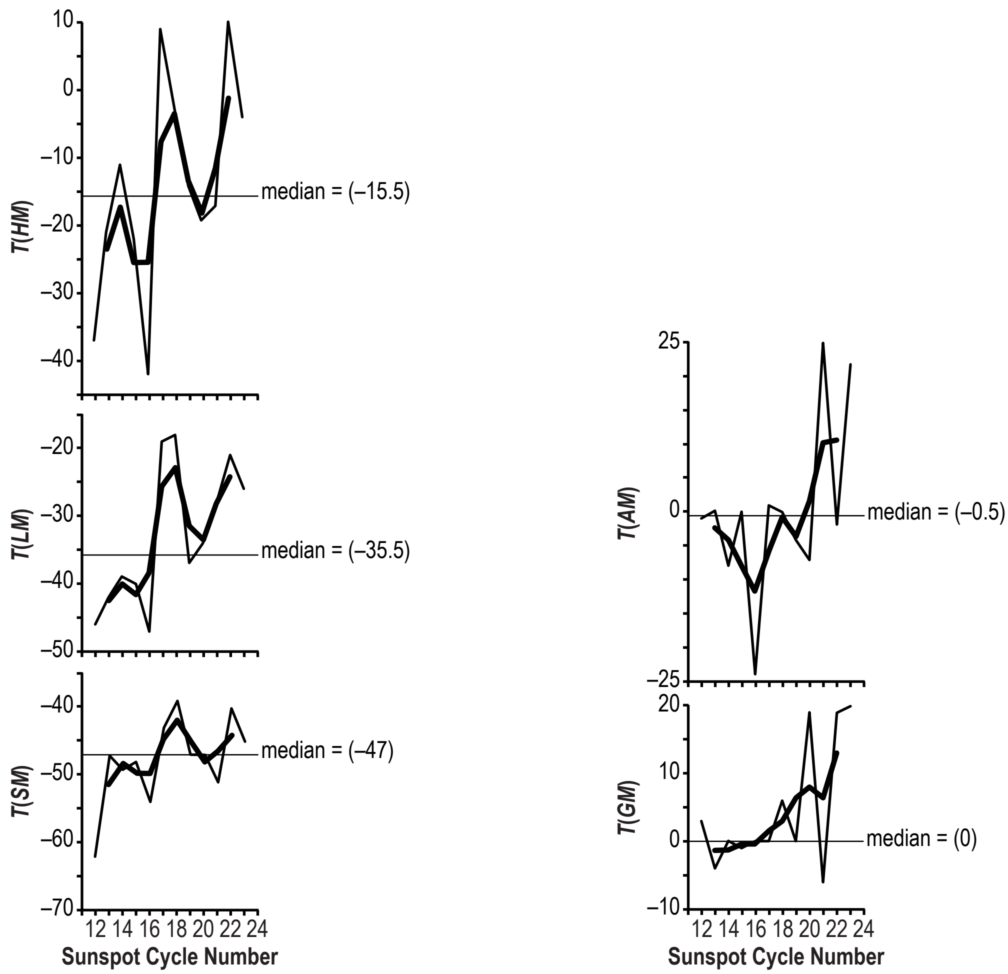

Figure 5. Cyclic variation of elapsed time in months of parametric maximum values relative to $E(RM)$ for cycles 12–23.

is 56 (cycle 21) to 103 mo (cycle 20). Through December 2007, cycle 23's fall time based on A is 71 mo, with only cycle 21's fall time being shorter. For $t(LM–Lm)$, the median is 98 mo and the range is 83 (cycle 18) to 124 mo (cycle 13). For cycle 23, the value will measure 112 mo, presuming Lm for cycle 24 occurred in May 2007, and the two-cycle moving average for cycle 22's fall time will measure 102.8 mo. For $t(HM–Hm)$, the median is 76 mo and the range is 57 (cycle 17) to 103 mo (cycle 13). For cycle 23, the value will measure 91 mo, presuming Hm for cycle 24 occurred in June 2007, and the two-cycle moving average for cycle 22's fall time will measure 73.5 mo.

Figure 8 shows the cyclic variation of the minimum-to-minimum periods, or length or duration in months (Period) for each of the parameters. For Period ($Rm–Rm$), the median is 125 mo and its range is 116 (cycle 22) to 142 mo (cycle 13). Cycles 12–14, 22, and 23 are longer period cycles (≥135 mo), while cycles 15–19, 21, and 22 are shorter period cycles (≤126 mo). As previously noted in the Introduction, the length of cycle 23 already measures 140 mo (through December 2007) and this value is within 2 mo of equaling the longest known period of a sunspot cycle during the

Table 3. Parametric epochal lead/lag times relative to $E(RM)$.

Cycle	*T*(*GM*)	*T*(*AM*)	*T*(*LM*)	*T*(*HM*)	*T*(*SM*)	*T*(*Lm*)	*T*(*Hm*)
12	3	–1	–46	–37	–62	–63	–63
13	–4	0	–42	–21	–47	–71	–68
14	0	-8	–39	–11	–49	–63	–63
15	–1	0	–40	–22	–48	–62	–62
16	0	–24	–47	–42	–54	–78	–81
17	0	1	–19	9	–43	–45	–50
18	6	0	–18	–3	–39	–54	–55
19	0	–4	–37	–14	–47	–65	–57
20	19	–7	–34	–19	–47	–78	–68
21	-6	25	–29	–17	–51	–49	–59
22	19	–2	–21	10	–40	–40	–58
23	20	22	–26	–4	–45	–52	–54
All Cycles: 12-23							
med	0	–0.5	–35.5	–15.5	–47	–62.5	–60
mean	4.7	0.2	–33.2	–14.3	–47.7	–60.0	–61.5
sd	9.3	12.9	10.3	15.9	6.2	12.3	8.2
low	–6	–24	–47	–42	–62	–78	–81
high	20	25	–18	10	–39	–45	–50
ad	7.6	7.9	8.8	12.1	4.3	10.0	6.0

Note: Negative values mean parametric epoch leads *E*(*RM*). Positive values mean parametric epoch lags *E*(*RM*).

modern era (142 mo by cycle 13; cycle 9 had a period of 149 mo and cycles 3–5 had periods of 164, 147, and 153 mo, respectively, but these cycles are not as reliably determined as cycles from cycle 12 onwards). Based on cycles 12–14 and 20 (those of longer period), the 90-percent prediction interval for cycle 23's period is 139±6.9 mo, inferring that cycle 24's conventional onset (based on 12-mma values of *R*) is expected no later than about July 2008 (there is only a 5-percent chance that it will occur after July 2008).

For Period(*Gm*–*Gm*), the median is also 125 mo and the range is 120 (cycle 15) to 147 mo (cycle 13). Through December 2007, Period(*Gm*–*Gm*) for cycle 23 measures 137 mo. For Period(*Am*–*Am*), the median is 126 mo and the range is 116 (cycle 22) to 147 mo (cycle 14). Through December 2007, Period(*Am*–*Am*) for cycle 23 measures 140 mo. For Period(*Lm*–*Lm*), the median is 119 mo and the range is 112 (cycle 15) to 162 mo (cycle 20). Through May 2007, Period(*Lm*–*Lm*) for cycle 23 measures 138 mo. For Period(*Hm*–*Hm*), the median is 128 mo and the range is 109 (cycle 15) to 150 mo (cycle 13). Through June 2007, Period(*Hm*–*Hm*) for cycle 23 measures 141 mo. It can be seen in figure 8 that all parametric periods appear to behave quite similarly (based on the two-cycle moving averages), decreasing in length from cycle 13 through about cycles 16–18 and increasing in length thereafter through cycle 20 and then decreasing again through cycle 21 (possibly through cycle 22, except for Period(*Hm*–*Hm*)).

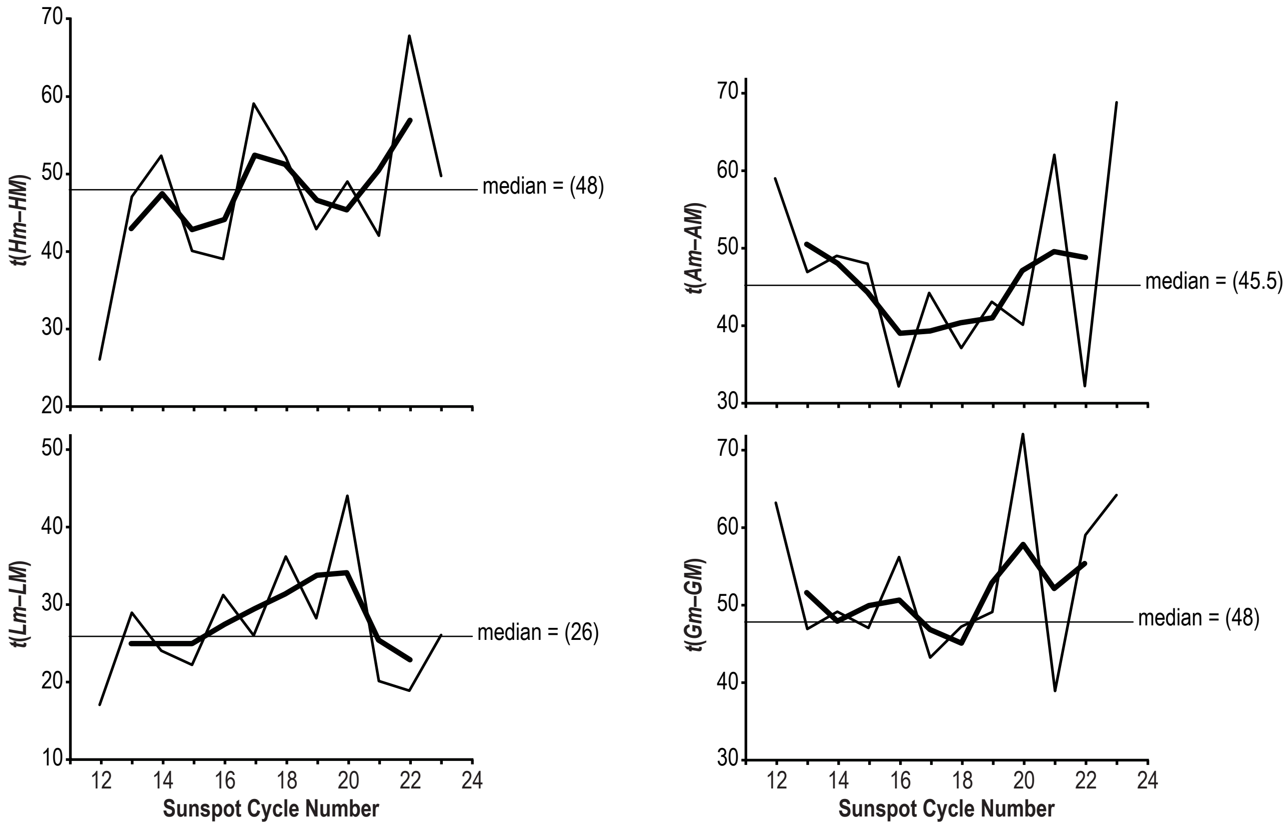

Figure 6. Cyclic variation of elapsed time in months from minimum to maximum parametric value for cycles 1–23 (rise times).

Figure 9 shows the cyclic variation of the maximum to maximum periods for each of the parameters. For Period(*RM*–*RM*), the median is 128 mo and the range is 108 (cycle 16) to 145 mo (cycle 13). The conventional maximum amplitude based on *R* for cycle 23 occurred in April 2000, inferring that *RM* for cycle 24 should be expected probably sometime in 2011 or later. For Period(*GM*–*GM*), the median is 129 mo and the range is 108 (cycle 16) to 149 mo (cycle 13). The conventional maximum amplitude based on *G* for cycle 23 occurred in December 2001, inferring that *GM* for cycle 24 should be expected probably sometime in 2012. For Period(*AM*–*AM*), the median is 126 mo and the range is 88 (cycle 21) to 165 mo (cycle 20). The conventional maximum amplitude based on *A* for cycle 23 occurred in February 2002, inferring that *AM* for cycle 24 should be expected probably sometime in 2012. For Period(*SM*–*SM*), the median is 126 mo and the range is 119 (cycle 16) to 143 mo (cycle 13). The conventional maximum amplitude based on *S* (associated with cycle minimum occurrence) for cycle 23 occurred in July 1996. Through December 2007, Period(*SM*–*SM*) for cycle 23 equals 138 mo, well longer than the median with only two cycles having longer Period(*SM*–*SM*) values, cycles 13 (143 mo) and 14 (139 mo). So, it seems that cycle minimum for cycle 24 is most imminent (occurring before July 2008). For Period(*LM*–*LM*), the median is 125 mo and the range is 111 (cycle 18) to 148 (cycle 13). The conventional maximum amplitude based on *L* for cycle 23 occurred in February 1998. Through December 2007, Period(*LM*–*LM*)

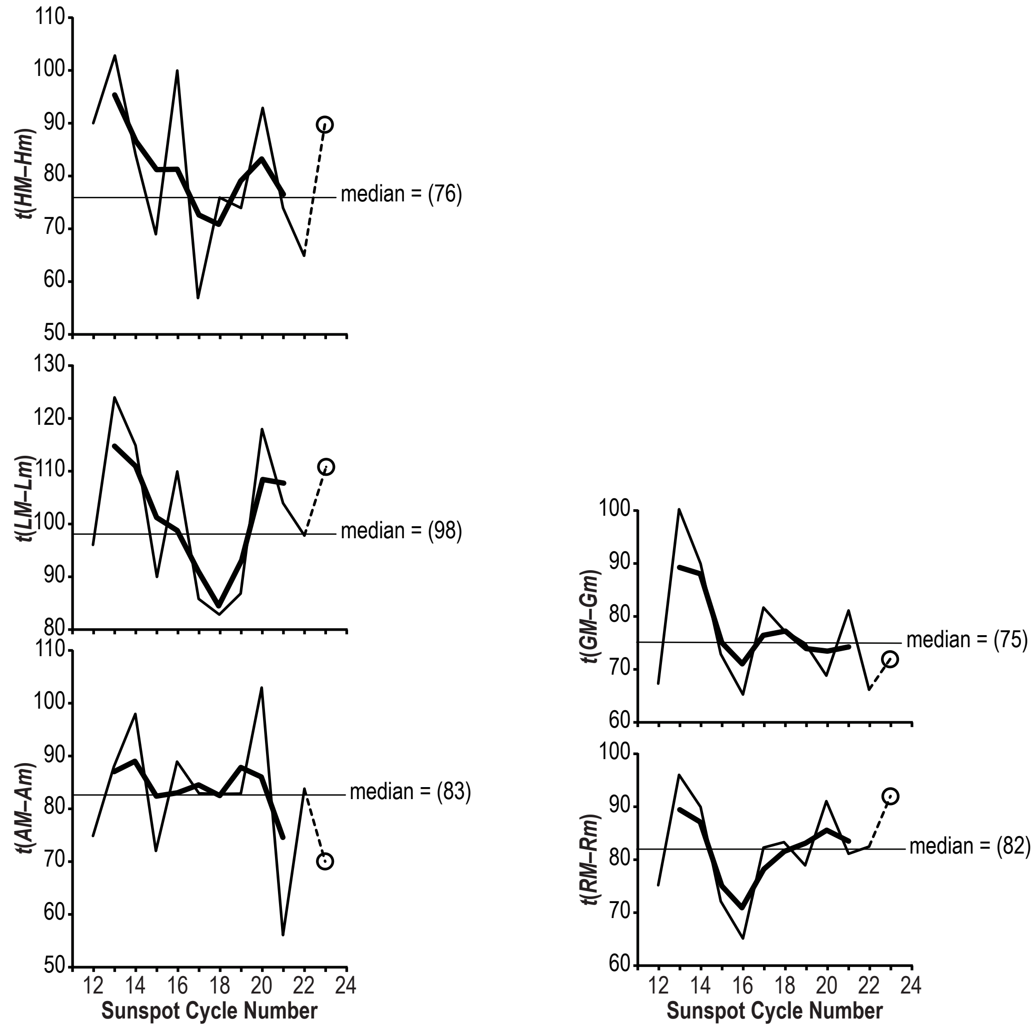

Figure 7. Cyclic variation of elapsed time in months from maximum to succeeding cycle minimum parametric value for cycles 12–23 (fall times).

for cycle 23 equals 118 mo, with only cycle 18 having a shorter Period(*LM*–*LM*). So, it seems that several months or more remain before *LM* for cycle 24 occurs, inferring that *LM* for cycle 24 should be expected probably sometime in late 2008 to early 2009. For Period(*HM*–*HM*), the median is 127 mo and its range is 108 (cycle 15) to 159 mo (cycle 16). The conventional maximum amplitude based on *H* for cycle 23 occurred in December 1999. Through December 2007, Period(*HM*–*HM*) for cycle 23 equals 97 mo. So, it seems that several months or more remain before *HM* for cycle 24 occurs, inferring that *HM* for cycle 24 should be expected probably sometime in 2010 or later.

Table 4 summarizes the rise and fall times and minimum-to-minimum and maximum-to-maximum periods for each of the parameters discussed and visualized in figures 6–9. As before, the statistics are given at the bottom.

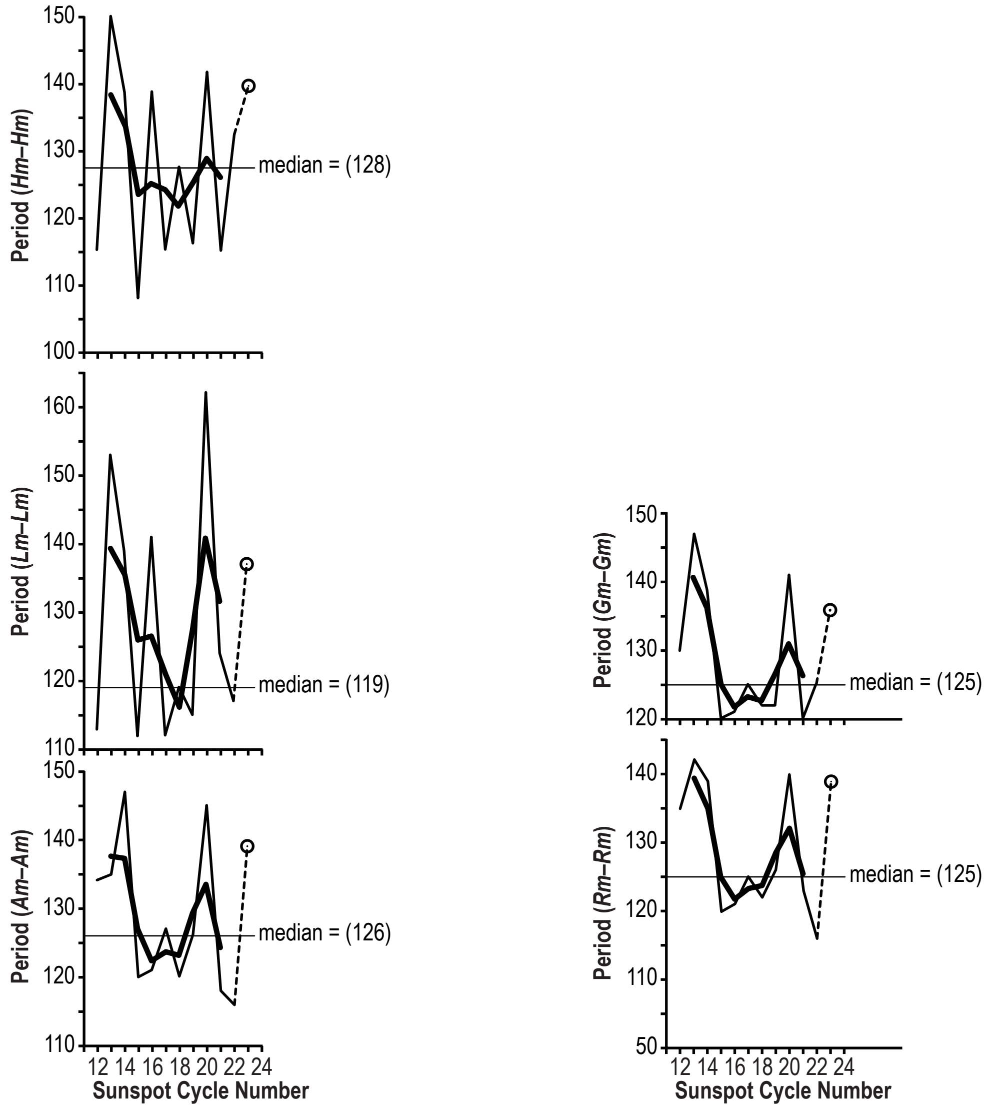

Figure 8. Cyclic variation of elapsed time in months from minimum to succeeding cycle minimum parametric value for cycles 12–23 (minimum-to-minimum periods).

2.2 Correlative Relationships

Figure 10 depicts the scatter plots of (a) *Rm* and (b) *RM* versus the parametric minimum values. Also given in each are the inferred regression line (the diagonal lines), the medians (the horizontal and vertical lines), the coefficient of correlation (*r*) and the probability (*P*) of obtaining the observed result or one more suggestive of a departure from independence (chance) based on Fisher's exact test for 2×2 contingency tables.[20] Cycles 16, 19, and 22 are identified in some of the panels as having behaviors suggesting that they might be regarded as statistical outliers at times.

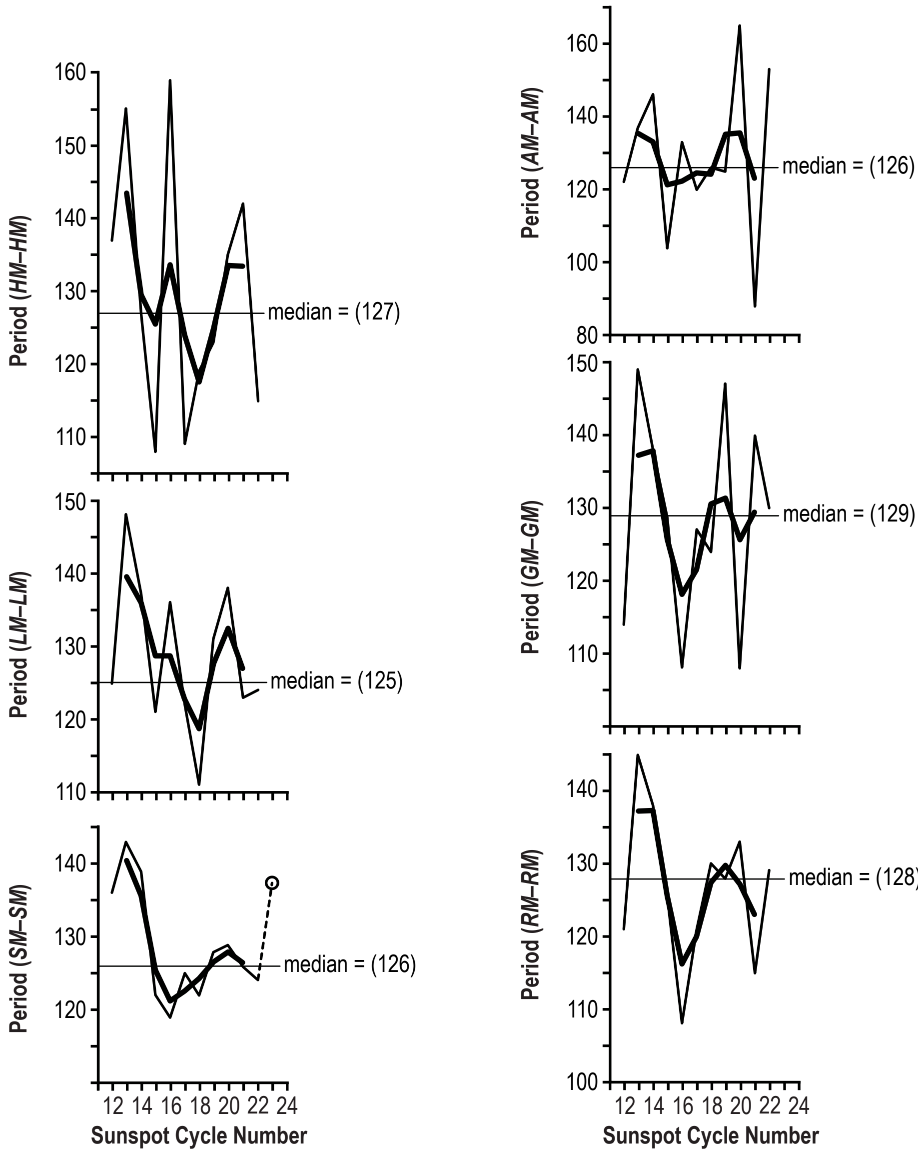

Figure 9. Cyclic variation of elapsed time in months from maximum to succeeding cycle maximum parametric value for cycles 12–22 (maximum-to-maximum period).

For cycle 24, the tentative minimum values (see table 1) for *Gm*, *Lm,* and *Hm* lie to the left of the parametric median, suggesting a lower than median value for *Rm* for cycle 24, which is true (*R* measures 5.0 in December 2007, as compared to the median value of *Rm*, which equals 5.3). For *Am* and *SM*, the tentative values lie above their respective medians. For *Am*, this would ordinarily indicate an *Rm* equal to 5.3 or higher, which is not the case. For *SM*, this indicates an *Rm* below the median, in agreement with *Gm*, *Lm*, and *Hm*.

Table 4. Rise and fall times and lengths (periods) of cycles.

	Rise Time (*m–M*)					Fall Time (*M–m*)*					Periods (*m–m*)*					Periods (*M–M*)					
Cycle	**R**	**G**	**A**	**L**	**H**	**R**	**G**	**A**	**L**	**H**	**R**	**G**	**A**	**L**	**H**	**R**	**G**	**A**	**L**	**H**	**S**
12	60	63	59	17	26	75	67	75	96	90	135	130	134	113	116	121	114	122	125	137	136
13	46	47	47	29	47	96	100	88	124	103	142	147	135	153	150	145	149	137	148	155	143
14	49	49	49	24	52	90	90	98	115	87	139	139	147	139	139	138	137	146	137	127	139
15	48	47	48	22	40	72	73	72	90	69	120	120	120	112	109	128	129	104	121	108	122
16	56	56	32	31	39	65	65	89	110	100	121	121	121	141	139	108	108	133	136	159	119
17	43	43	44	26	59	82	82	83	86	57	125	125	127	112	116	121	127	120	122	109	125
18	39	45	37	36	52	83	77	83	83	76	122	122	120	119	128	130	124	126	111	119	122
19	47	47	43	28	43	79	75	83	87	74	126	122	126	115	117	128	147	125	131	123	128
20	49	72	42	44	49	91	69	103	118	93	140	141	145	162	142	133	108	165	138	135	129
21	42	39	62	20	42	81	81	56	104	74	123	120	118	124	116	115	140	88	123	142	126
22	34	59	32	19	68	82	66	84	98	65	116	125	116	117	133	129	130	153	124	115	124
23	47	64	69	26	50	(93)	(73)	(71)	(112)	(91)	(140)	(137)	(140)	(138)	(141)	-	-	-	-	-	(138)
All Cycles: 12-23																					
med.	47	48	45.5	26	48.0	82	75	83	98	76	125	125	126	119	128	128	129	126	125	127	126
mean	46.7	52.6	47.0	25.4	47.3	81.5	76.8	83.1	101.0	80.7	128.1	128.4	128.1	127.9	127.7	126.9	128.5	129.0	128.7	129.9	128.5
sd	7.0	10.0	11.5	10.6	10.6	8.9	10.9	12.7	14.2	14.8	9.2	9.6	10.8	17.9	13.6	10.4	14.3	21.7	10.4	17.4	7.7
low	34	39	32	17	26	65	66	56	83	57	116	120	116	112	109	108	108	88	111	108	119
high	60	72	69	44	68	96	100	103	124	103	142	147	147	162	150	145	149	165	148	159	143
ad	4.9	8.8	8.7	5.6	7.8	6.4	8.3	8.5	12.0	12.6	7.9	7.9	8.8	15.2	11.8	7.8	11.1	16.2	8.4	14.3	6.0

*Median, mean, *sd*, low, high, and *ad* excludes cycle 23 potential values.

All of the linear fits for estimating *Rm* are statistically significant, except for the one based on *Lm*. Removal of cycle 22 (a statistical outlier) results in a statistically important fit, having r=0.740. (Because *Lm* and *Hm* always occur prior to *Rm*, they are the only precursor parameters that can be used to forecast *Rm* in advance. The others provide a current running estimate of *Rm*. Using the modified regression for *Lm*, *Rm* for cycle 24 is estimated to be about 3.4, while using the derived regression based on *Hm*, *Rm* for cycle 24 is estimated to be about 3.8. The value of *R* in December 2007 is 5.0.)

Of the various fits of *RM* versus parametric minimum values, the only one that is statistically important is the one based on *Hm*. Using the tentative value for cycle 24 (11.7) suggests *RM* for cycle 24 should measure about 103.2±65.1, the 90-percent prediction interval, inferring only a 5-percent chance that *RM* for cycle 24 will exceed 168.3. Removal of cycles 19 and 16 (statistical outliers) improves the fit to r=0.873 and, using this modified fit, *RM* for cycle 24 is estimated to be about 99.0±33.4, the 90-percent prediction interval, inferring only a 5-percent chance that *RM* for cycle 24 will exceed 132.4. It should be noted that all of the fits become statistically important by removing those cycles considered to be statistical outliers, particularly cycle 19, in the fits against *Gm*, *Am*, and *SM* and cycles 19 and 22 in the fit against *Lm*. Using the resultant modified fits, RM for cycle 24 is estimated (90-percent prediction intervals) to be ≤106.7±46.1 based on *Gm*(r=0.727); ≤115.2±40.1 based on *Am*(r=0.797); and ≤109.6±48.2 based on *SM*(r=–0.697). The "less than or equal to" symbol simply denotes that the estimates are based on tentative values that might slightly decrease in value as time progresses.

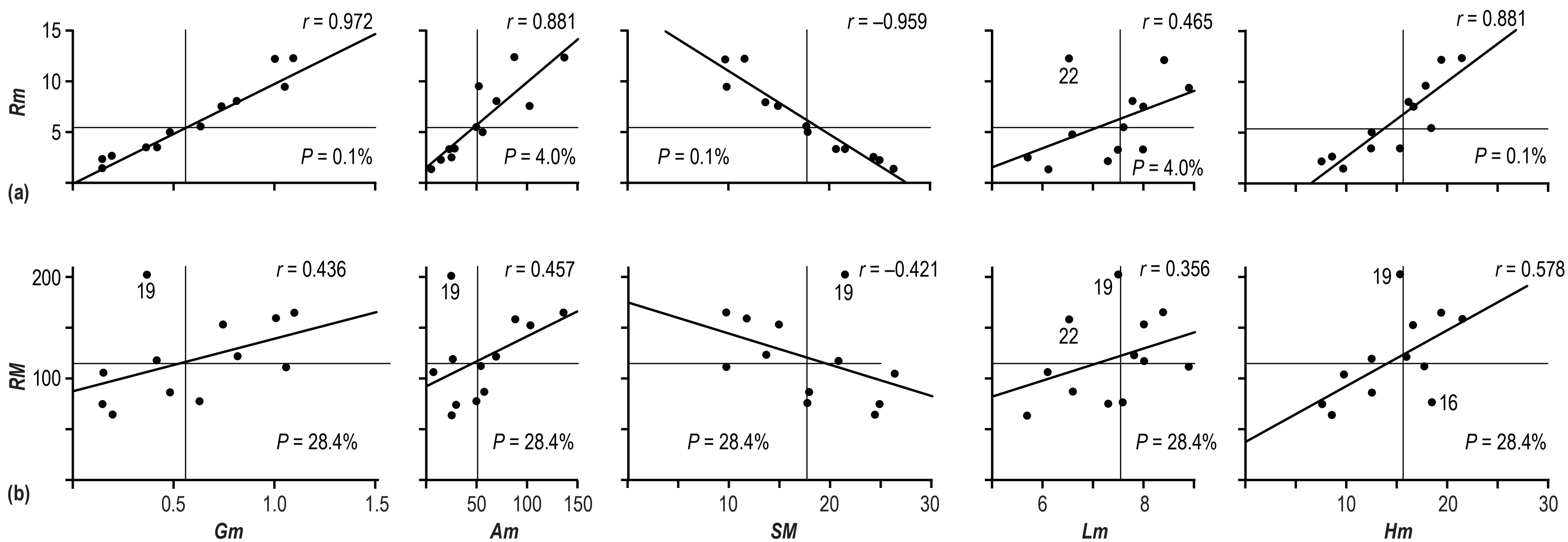

Figure 10. Scatter plots of (a) *Rm* and (b) *RM* versus parametric minimum values.

Figure 11(a) depicts the scatter plots of *RM* versus parametric maximum values. Figure 11 (b) depicts *RM* versus *ASC*(=*t*(*Rm*–*RM*)), *PER*(cycle *n*–1), where *PER* is Period(*Rm*–*Rm*), and *Rm*. Of the fits displayed in 11(a) the ones based on *GM* and *AM* are the most statistically important (*cl* >99.9 percent). The one based on *HM* is statistically important (*cl* >95 percent), while the one based on LM is only of marginal statistical importance (*cl* >90 percent). Both the fits based on *LM* and *HM* can be improved by removing the statistical outliers, cycles 21 and 16 in the *LM* fit (*r*=0.830) and cycle 15 in the *HM* fit (*r*=0.951). Thus, if in the course of the rise of cycle 24 *LM* exceeds 24 deg, it would be expected that *RM* >131, while if *HM* exceeds 38 deg, then it would be expected that *RM* >127. Similarly, if *GM* and *AM* exceed 10 and 2,000, then it would be expected that cycle 24's *RM* >117 and >118, respectively. Close monitoring of the 12-mma values of the parameters will provide continuous estimation of *RM*.

Of the fits displayed in figure 11(b), only the one based on *ASC* is statistically important, although all can be greatly improved by removal of one or more cycles (statistical outliers). For example, removal of cycles 19 and 14 (*RM* extreme events) in the fit of *RM* versus *ASC* yields a fit that is highly statistically important at *cl* >99.9 percent (*r*=–0.875). Removal of cycle 19 in the fit of *RM* versus *Rm* yields a fit that is also highly statistically important at *cl* >99.5 percent (*r*=0.779). Removal of cycles 16, 19, and 21 in the period-amplitude fit yields a fit that is statistically important at *cl* >95 percent (*r*=–0.711), as well. Because *Rm* for cycle 24 will be below the median, statistically speaking, it should be expected that *RM* for cycle 24 would also be below the median, unless of course cycle 24 turns out to be another statistical outlier as is cycle 19, the largest cycle of the modern era. The same can be said based on the amplitude-period fit. Because the period of cycle 23 is longer than the median, this too suggests that *RM* for cycle 24 will be smaller than the median (an exception is cycle 21, having the second largest *RM* in modern time).

Table 5 identifies the statistically important fits shown in figures 10 and 11, giving the coefficient of correlation (*r*); the coefficient of determination (r^2), which is a measure of the amount of variance explained by the inferred regression; the y-intercept of the inferred regression (*a*); the slope of the inferred regression (*b*); the standard error of estimate (*se*); and the confidence level of the inferred regression (*cl*). At the bottom are the means and standard deviations (*sd*) of *Rm*, and *RM*, for comparison. (The inferred regressions have not been modified by removing statistical outliers.)

2.3 Superposed Epoch Analysis

Figure 12 depicts the results of superposed epoch analyses of cycles 12–23, using *E*(*Rm*) as the epoch of superposition and examining the interval 30 mo prior to *E*(*Rm*) to 12 mo after *E*(*Rm*) for each of the parameters (12-mma values). To the right of each panel is the parametric mean and *sd* for *t*=0. For *G*, *A*, *S*, *L*, and *H*, the occurrences of cyclic minimum are identified along adjacent horizontal lines and for all parameters the mean and range (low and high values) are identified along adjacent vertical lines (mean values are represented by the tick marks about midway along the vertical lines). Obviously, the minimum values of *G* and *A* almost always occur simultaneously with *E*(*Rm*), with 7 of 12 cycles having *Gm* and *Rm* occurring simultaneously, and 10 of 12 cycles having *Am* and *Rm* occurring within 2 mo of each other. Similarly, 10 of 12 cycles have had their maximum number of spotless days within 2 mo of *Rm* occurrence.

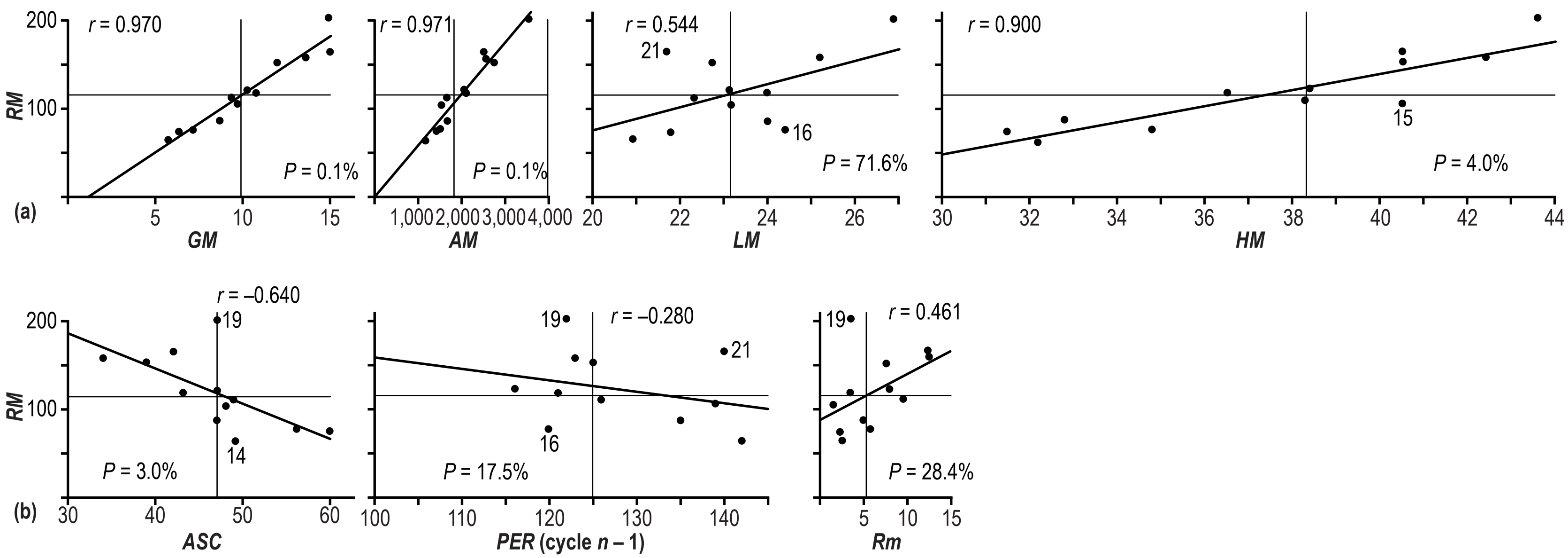

Figure 11. Scatter plots of (a) *RM* versus parametric maximum values and (b) *RM* versus *ASC*, *PER*(cycle *n*–1), and *Rm*.

Table 5. Summary of statistically important correlations (*cl* >90 percent).

Correlation	*r*	r^2	*a*	*b*	*se*	*cl*
Rm vs. *Gm*	0.972	0.945	–0.112	10.586	0.932	>99.9
RM vs. *AM*	0.971	0.943	0.140	0.059	1.075	>99.9
RM vs. *GM*	0.970	0.942	–14.289	13.107	10.624	>99.9
Rm vs. *SM*	–0.959	0.919	17.134	–0.620	1.138	>99.9
RM vs. *HM*	0.900	0.809	–227.881	9.229	19.200	>99.9
Rm vs. *Am*	0.881	0.777	1.463	0.085	1.905	>99.9
Rm vs. *Hm*	0.881	0.776	–4.982	0.754	1.881	>99.9
RM vs. *ASC*(*R*)	–0.640	0.441	299.817	–3.859	33.809	>95
RM vs. *Hm*	0.578	0.334	39.307	5.459	35.910	>95
RM vs. *LM*	0.544	0.296	–199.072	13.654	36.893	>90

Note: $\langle Rm \rangle = 6.1$, $sd = 3.8$ $\langle RM \rangle = 119.7$, $sd = 41.9$

Table 6 displays the monthly means and 12-mma of the parameters for late cycle 23, from January 2004 through December 2007. Also given in the table is the ratio of the number of high-latitude spot groups to the total number of spot groups ($G(H)/G$, based on monthly counts), which will be discussed along with various comments in the next section.

Figure 13 shows the sum of the square of the deviations for each of the parameters as a function of elapsed time from $E(Rm)$, determined by comparing the 2007 data against the superposed curves, where December 2007 is considered t=0, then progressively incremented backwards (through t=–11). As an example, the sum of the square of the deviations for t=0 for R is $\sum d^2 = 12.65$, computed as follows: $\sum d^2 = (6.1-5.0)^2 + (6.5-5.7)^2 + \ldots + (12.7-12.0)^2 = 12.65$. For negative t, all sums of squares of the deviations are larger, inferring either that December 2007 is $E(Rm)$ for cycle 24 or a later date will mark its occurrence. For G, a minimum appears at t=–2, inferring that $E(Rm)$ might be expected about February 2008. For A, a minimum appears at t=–5, inferring that $E(Rm)$ might be expected about May 2008. For S, a minimum appears at t=–3, inferring that $E(Rm)$ might be expected about March 2008. For both L and H, minima appear at t=–9, inferring that $E(Rm)$ might be expected about September 2008. Thus, it appears that cycle 24 sunspot minimum should be expected about April/May 2008 (actually, sometime between February and September 2008), based on the sum of the squares of the parametric deviations in comparison to the superposed parametric curves.

2.4 The Ratio of $G(H)/G$ Relative to $E(Rm)$

Table 7 identifies Y to be the occurrences of high-latitude spot groups relative to $E(Rm)$ for cycles 12–23 for t equal to –30 to 12. When the ratio of the number of high-latitude spot groups to the total number of spot groups equals 0.50 or higher, an asterisk (*) appears beside the letter *Y*. The total number of cycles having high-latitude spots as a function of t appears to the right. As mentioned in section 2.1, the data were extracted from the Royal Greenwich Observatory and USAF/NOAA SOON data sets, available at NASA/Marshall Space Flight Center.[11]

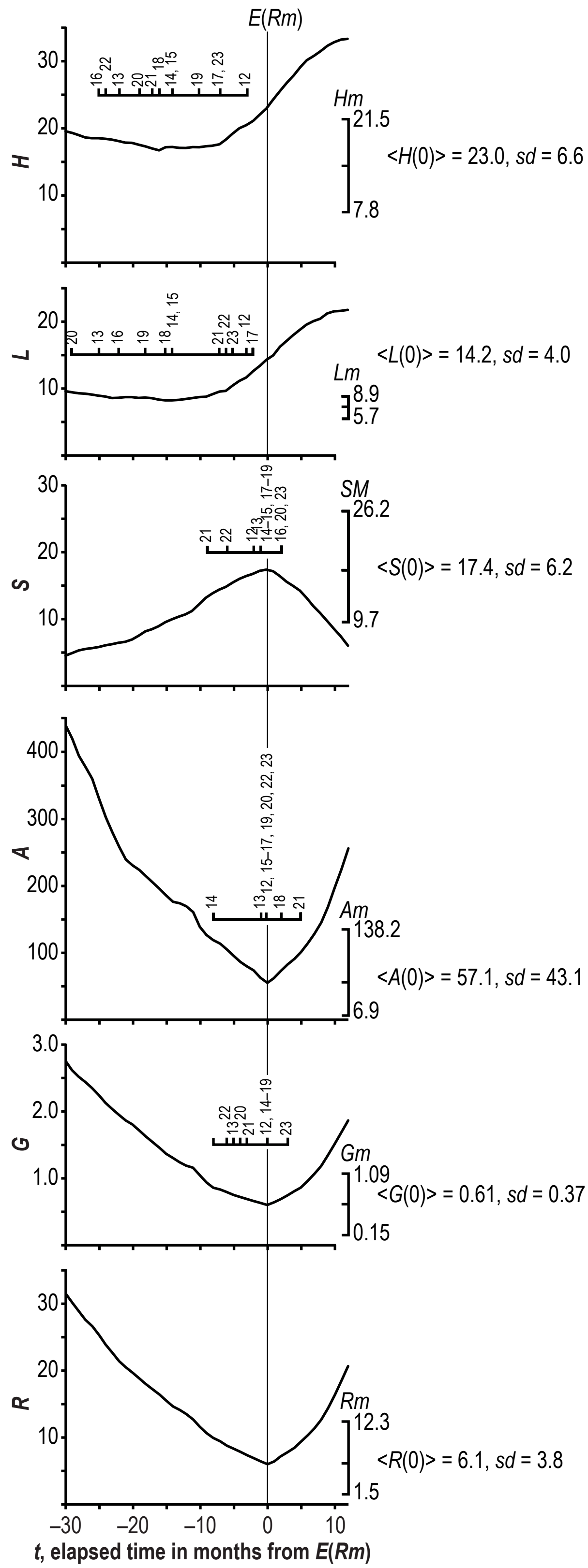

Figure 12. Superposed epoch analyses for *R*, *G*, *A*, *S*, *L*, and *H* for elapsed time (in months) from 30 mo before to 12 mo after *E*(*Rm*).

Table 6. Late cycle 23 parametric values (2004–present).

Monthly Values									12-mma Values							
t	Year	Mo	*R*	*G*	*A*	*L*	*H*	*S*	*R*	*G*	*A*	*L*	*H*	*S*	*G*(*H*)/*G*	Comments
92	2004	01	37.3	3.03	762.7	10.7	22	1	52.0	4.46	905.7	10.7	22.6	0.1	0.00	First spotless day for cycle 24
93	2004	02	45.8	4.28	619.9	10.7	24	0	49.3	4.19	910.1	10.5	21.4	0.1	0.00	
94	2004	03	49.1	4.16	700.0	11.8	19	0	47.1	3.98	910.8	10.4	20.5	0.1	0.00	
95	2004	04	39.3	3.47	439.6	11.5	20	0	45.5	3.88	844.2	10.5	20.0	0.2	0.00	
96	2004	05	41.5	4.29	627.3	9.4	19	0	43.8	3.82	745.5	10.5	19.5	0.3	0.00	
97	2004	06	43.2	4.03	584.2	11.3	16	0	41.6	3.68	697.6	10.5	19.0	0.3	0.00	
98	2004	07	51.1	3.71	1239.4	8.6	16	0	40.2	3.57	688.8	10.5	18.6	0.2	0.00	
99	2004	08	40.9	3.13	985.5	10.8	18	0	39.2	3.51	690.9	10.5	18.4	0.2	0.00	
100	2004	09	27.7	2.53	566.0	9.5	16	0	37.5	3.38	675.6	10.5	18.0	0.2	0.00	
101	2004	10	48.0	4.35	600.5	11.5	20	2	35.9	3.27	662.2	10.2	17.5	0.3	0.00	
102	2004	11	43.5	3.87	796.2	11.1	18	0	35.3	3.19	667.4	9.9	17.5	0.3	0.00	
103	2004	12	17.9	2.19	274.5	9.1	17	0	35.2	3.10	679.3	9.6	18.0	0.3	0.00	
104	2005	01	31.3	2.74	900.5	11.1	19	0	34.6	3.05	661.6	9.6	18.5	0.5	0.00	
105	2005	02	29.2	3.04	534.5	9.0	21	0	33.9	3.05	620.6	9.8	18.6	0.6	0.00	
106	2005	03	24.5	2.23	419.6	8.1	14	1	33.5	3.02	603.4	9.8	18.9	0.6	0.00	
107	2005	04	24.2	2.70	395.8	5.9	13	0	31.6	2.84	581.8	9.7	19.0	0.7	0.00	
108	2005	05	42.7	3.13	795.3	9.7	24	0	28.9	2.60	542.4	9.4	18.8	0.9	0.00	
109	2005	06	39.3	3.13	701.8	10.5	25	1	28.8	2.59	534.2	9.4	18.9	1.0	0.03	
110	2005	07	40.1	3.29	700.0	10.1	19	3	29.1	2.62	511.3	9.6	19.2	1.1	0.00	
111	2005	08	36.4	3.55	539.3	12.2	17	0	27.4	2.47	458.2	9.8	19.0	1.2	0.00	
112	2005	09	21.9	1.60	598.2	9.8	24	0	25.8	2.32	422.2	9.8	18.8	2.8	0.00	
113	2005	10	8.7	0.84	52.4	7.8	14	5	25.5	2.31	412.0	10.0	19.0	3.2	0.00	
114	2005	11	18.0	1.73	398.0	8.4	18	2	24.9	2.32	390.6	10.2	18.9	3.3	0.00	
115	2005	12	41.1	4.06	457.6	10.8	20	0	23.0	2.24	344.4	10.1	18.1	3.7	0.00	
116	2006	01	15.3	1.61	150.8	15.4	24	3	20.8	2.08	303.1	9.8	17.2	3.8	0.00	
117	2006	02	4.9	0.43	10.5	8.1	11	14	18.6	1.90	278.7	9.6	16.7	3.9	0.00	First occurrence of 10 or more spotless days
118	2006	03	10.6	1.35	78.5	8.9	18	10	17.4	1.81	258.3	9.7	16.3	4.2	0.00	
119	2006	04	30.2	3.23	490.8	10.5	16	0	17.1	1.83	243.3	9.8	16.6	4.5	0.00	
120	2006	05	22.3	2.90	188.7	11.2	18	4	17.3	1.85	249.9	9.8	16.9	4.7	0.00	
121	2006	06	13.9	1.33	197.0	6.2	12	5	16.3	1.74	250.9	9.5	16.3	5.1	0.00	
122	2006	07	12.2	1.35	214.6	6.3	10	2	15.3	1.65	256.1	8.8	15.5	5.3	0.00	
123	2006	08	12.9	1.13	438.5	11.6	14	4	15.6	1.70	273.4	8.4	15.2	4.8	0.00	
124	2006	09	14.4	1.83	210.4	11.8	18	2	15.6	1.72	279.7	8.2	15.1	4.7	0.00	
125	2006	10	10.5	1.13	79.5	9.0	26	10	14.2	1.58	263.2	8.1	14.9	5.7	0.03	
126	2006	11	21.4	1.90	528.8	6.2	14	3	12.7	1.39	249.2	7.9	14.6	6.6	0.00	
127	2006	12	13.6	1.35	370.3	5.9	10	8	12.1	1.31	251.0	7.9	14.5	6.8	0.00	
128	2007	01	16.9	2.06	377.6	5.4	14	0	12.0	1.29	251.2	8.0	14.6	7.3	0.00	
129	2007	02	10.6	1.36	200.5	6.5	13	6	11.6	1.26	234.6	7.7	14.4	7.8	0.00	
130	2007	03	4.8	0.77	41.6	6.7	15	14	10.8	1.18	211.0	7.2	13.8	8.8	0.00	
131	2007	04	3.7	0.47	132.6	10.2	14	21	9.9	1.07	199.6	6.7	12.6	10.3	0.00	First occurrence of 20 or more spotless days

Table 6. Late cycle 23 parametric values (2004–present) (continued).

Monthly Values									12-mma Values							
t	Year	Mo	*R*	*G*	*A*	*L*	*H*	*S*	*R*	*G*	*A*	*L*	*H*	*S*	*G*(*H*)/*G*	Comments
132	2007	05	11.7	1.13	209.6	7.7	13	4	8.7	0.96	174.7	6.6	11.7	12.0	0.00	Beginning of upturn in *L*?
133	2007	06	12.0	1.17	220.2	8.2	13	11	7.7	0.74	143.1	6.8	11.7	13.0	0.00	Beginning of upturn in *H*?
134	2007	07	10.0	0.97	193.3	6.3	12	8	7.0	0.77	118.3	7.2	12.3	14.0	0.00	
135	2007	08	6.2	0.77	64.1	5.6	8	8	6.1	0.66	95.1	7.5	12.9	15.5	0.00	
136	2007	09	2.4	0.33	15.4	5.2	9	22	5.9	0.62	91.4	7.5	12.7	16.3	0.00	
137	2007	10	0.9	0.10	4.5	4.4	6	28	6.1	0.63	91.4	7.5	13.1	16.4	0.00	
138	2007	11	1.7	0.20	5.2	8.7	13	24	5.7	0.59	78.8	7.7	14.4	17.1	0.00	
139	2007	12	10.1	0.74	135.9	8.6	10	13	5.0	0.51	61.7	7.9	15.0	18.1	0.00	
140	2008	01	3.4	0.39	14.4	11.7	30	19							0.10	First high-latitude new cycle spot
141	2008	02	2.1	0.28	8.7	6.4	10	22							0.00	
142	2008	03	9.3	0.97	144.5	8.3	13	17							0.00	
143	2008	04	2.9	0.43	29.0	8.6	27	20							0.07	
144	2008	05	2.9	0.26	11.1	13.4	31	22							0.06	
145	2008	06	3.1	0.07	9.4	6.1	10	18							0.00	

Note: Since January 1977, *A* has been increased by 1.4X to compensate for change in areal determination methodology (visual determination now as compared to photographic determination prior to 1977). The ratio of the number of high-latitude groups to the total number of groups per month is *G*(*H*)/*G*. When ratio equals or exceeds 0.50, one infers dominance of new cycle over old cycle. A high-latitude group is one having latitude equal to or exceeding 25 deg.

Clearly, as sunspot minimum approaches, the frequency of high-latitude spot groups increases, sometimes first becoming dominant several months prior to sunspot minimum (cycle 21 at t=–8) and sometimes several months after sunspot minimum (cycle 12 at t=7). In fact, cycle 23 did not have its first appearance of dominant high-latitude spot groups until t=13 (June 1997). Cycles 13–16 and 19–21 had first appearances of high-latitude spot group dominance during the interval $-8 \leq t \leq 0$, while cycles 12, 17, 18, 22, and 23 had first appearances of high-latitude spot group dominance during the interval of $3 \leq t \leq 13$. So, first appearance of high-latitude spot group dominance, in itself, seems a poor descriptor for determining when sunspot minimum occurs (that is, the official onset for a sunspot cycle should not be defined by the first appearance of high-latitude spot group dominance).

Figure 14 displays the cyclic variation of the first appearance of high-latitude spot group dominance, following the same format as used in figures 1–8. A striking pattern seems apparent; namely, a three-cycle variation in the first appearances seems apparent. The median is t=–1. Cycles 13–15 had first appearances before sunspot minimum (3–6 mo). Cycles 16–18 had first appearance on or after sunspot minimum (0–6 mo). Cycles 19–21 had first appearances before sunspot minimum (2–8 mo). Cycles 22 and 23 had first appearances after sunspot minimum (3–13 mo). If this seemingly apparent pattern persists, then cycle 24 should have its first appearance of high-latitude spot group dominance after sunspot minimum to complete the inferred three-cycle variation.

2.5 Behavior of *R* in the Vicinity of Sunspot Minimum

Figure 15 depicts the cyclic variation of the elapsed time in months between the last occurrence of $R \geq 15$ prior to $E(Rm)$ (a), the elapsed time in months between $E(Rm)$ and the first

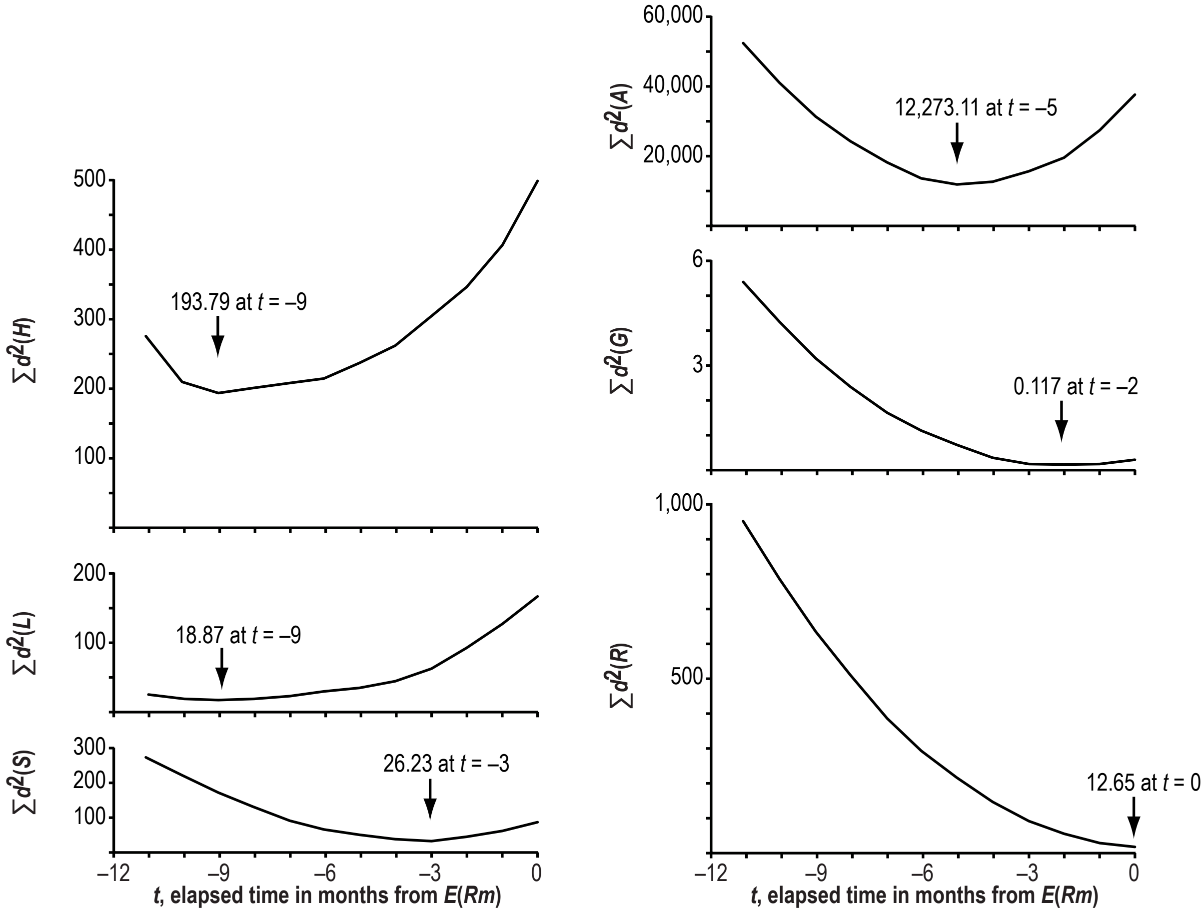

Figure 13. Variation of the sum of the square of the deviations for R, G, A, S, L, and H, comparing 2007 parametric data with the supposed parametric curves.

occurrence of $R \geq 15$ (b) and the cumulative elapsed time in months when $R \geq 15$ is in the vicinity of sunspot minimum, numerically equal to the sum of the two previous elapsed times (c). The time between last occurrence of $R \geq 15$ and $E(Rm)$ has drastically decreased from cycle 12/13 (about 40 mo) to a minimum in cycle 21 (about 5 mo). Each of cycles 12–17 had elapsed time in months of last occurrence of $R \geq 15$ to $E(Rm)$ longer than the median (13 mo). Each of cycles 18–23 had elapsed time in months of last occurrence of $R \geq 15$ to $E(Rm)$ shorter than the median. Through December 2007, the elapsed time for cycle 24 measures 15 mo. Presuming that cycle 23 will have a two-cycle moving average equal to the computed value for cycle 18 (11.75), it can be concluded that $E(Rm)$ for cycle 24 lies 20 mo from September 2006 (the last occurrence of $R \geq 15$ prior to $E(Rm)$ for cycle 24), or about May 2008.

Likewise, the elapsed time in months from $E(Rm)$ to the first occurrence of $R \geq 15$, while being relatively flat for cycles 12–19 has decreased from above the median (9.5 mo) to below the median, the lowest occurring in cycle 22 (3 mo) The trend should now be either flat or slightly upward. Presuming that cycle 23 will have a two-cycle moving average equal to the computed value for cycle 19 (8.25), it can be concluded that the first occurrence of $R \geq 15$ will occur about 8 mo after $E(Rm)$ for cycle 24. To date, it has never exceeded 15 mo.

Table 7. Occurrences of high-latitude spots relative to $E(Rm)$.

	Cycle												
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Total**
–30									Y			Y	2
–29						Y				Y			2
–28								Y		Y			2
–27										Y			1
–26											Y		1
–25										Y			1
–24			Y			Y					Y		3
–23													0
–22					Y		Y						2
–21													0
–20	Y					Y				Y			3
–19	Y					Y				Y			3
–18											Y		1
–17											Y		1
–16											Y		1
–15		Y											1
–14					Y		Y				Y	Y	4
–13													0
–12									Y		Y		2
–11													0
–10									Y	Y			2
–9		Y			Y		Y			Y			4
–8				Y						Y*	Y		3
–7			Y	Y					Y	Y			4
–6				Y*					Y				2
–5		Y		Y*	Y				Y				4
–4			Y*				Y		Y		Y		4
–3		Y*			Y			Y	Y*	Y			5
–2		Y			Y			Y*			Y		4
–1		Y*		Y*	Y				Y	Y	Y		6
0		Y*	Y		Y*				Y	Y	Y	Y	7
1		Y			Y	Y	Y	Y*	Y	Y	Y	Y	9
2		Y*	Y		Y			Y	Y	Y	Y	Y	8
3		Y*		Y*	Y*			Y	Y	Y*	Y*	Y	8
4	Y	Y*	Y*		Y*	Y	Y	Y*	Y	Y	Y*	Y	11
5		Y*	Y*		Y*	Y	Y*	Y	Y*	Y	Y	Y	10
6	Y*	Y		Y*	Y*	Y*	Y	Y*	Y	Y	Y	Y	11
7	Y*	Y	Y	Y*	Y*	Y*	Y	Y*	Y	Y*	Y	Y	12
8	Y	Y		Y*	Y*	Y*	Y	Y	Y	Y	Y*	Y	11
9	Y*	Y	Y	Y*	Y*	Y		Y	Y	Y	Y*	Y	11
10	Y	Y		Y	Y*	Y	Y	Y	Y*	Y	Y*	Y	11

Table 7. Occurrences of high-latitude spots relative to $E(Rm)$ (continued).

	Cycle												
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**Total**
11	Y	Y		Y*	Y	Y*	Y	Y	Y*	Y	Y	Y	11
12		Y		Y	Y	Y	Y	Y*	Y	Y	Y*	Y	10

Note: Y means yes; * means $G(H)/G$ is 0.50 or larger, where $G(H)$ means the monthly number of groups at high latitude (greater than or equal to 25 deg) and G is the monthly number of groups (all latitudes). Cycle 23's $G(H)/G$ did not meet or exceed 0.50 until t = 13 (June 1997).

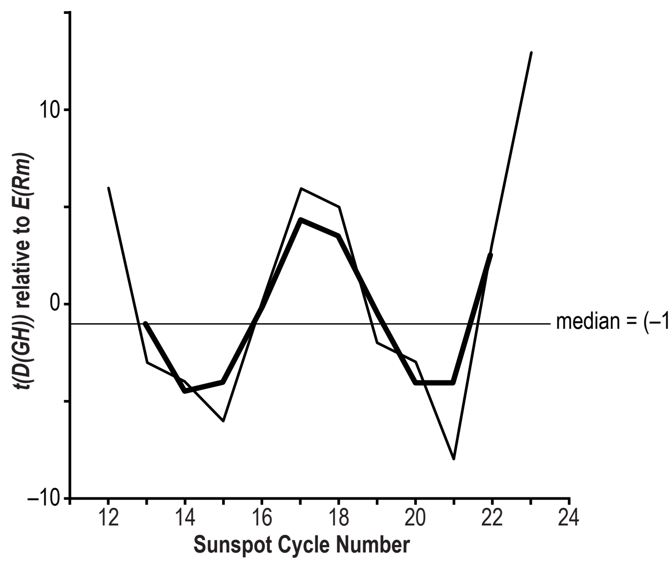

Figure 14. Cyclic variation of the first appearance of high-latitude spot group dominance relative to $E(Rm)$.

Regarding the cumulative elapsed time, its behavior is dominated by the elapsed time from last occurrence of $R \geq 15$ to $E(Rm)$. Cycles 12–17 have elapsed times longer than the median (22.5 mo), while cycles 18–23 have elapsed times shorter than the median. The trend appears to be reversing (towards longer elapsed time). Since the cumulative elapsed time is simply the sum of the two previously described elapsed times, it is expected that the cumulative elapsed time for cycle 24 to be about 28 mo, so that if $E(Rm)$ for cycle 24 is May 2008, then R should be ≥ 15 about January 2009 (in terms of 12-mo moving averages).

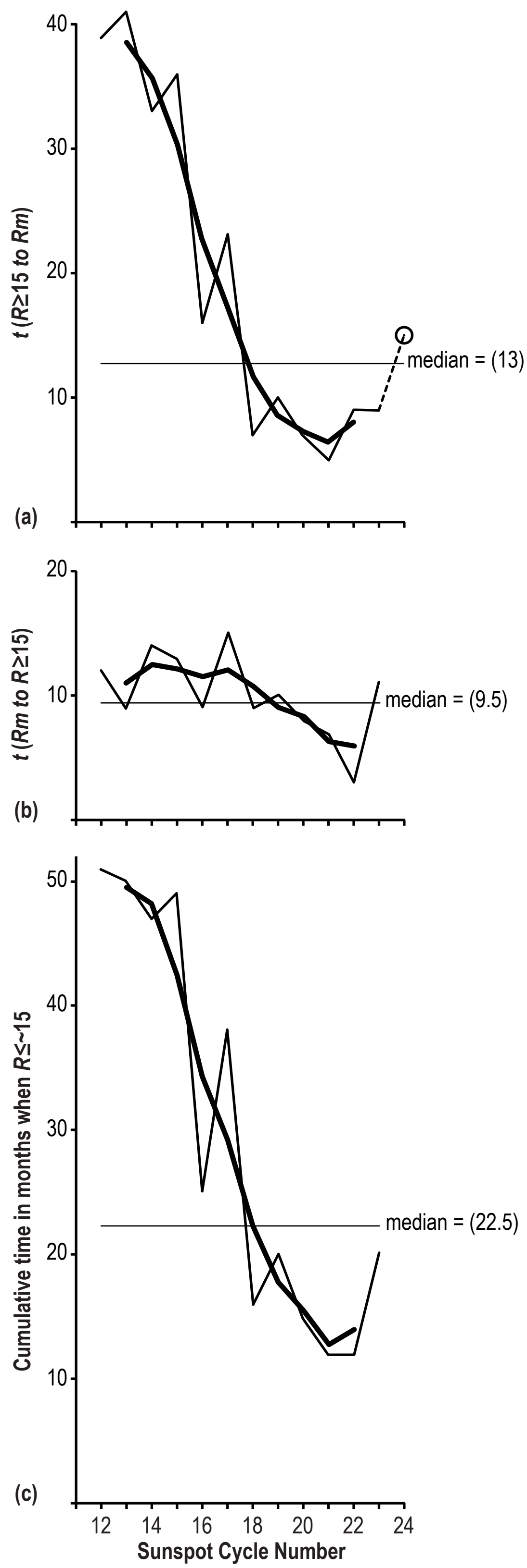

Figure 15. Cyclic variation of R in the vicinity of sunspot minimum: (a) between the last occurrence of $R \geq 15$ prior to $E(Rm)$; (b) between $E(Rm)$ and first occurrence of $R \geq 15$; and (c) when $R \leq 15$ is in the vicinity of sunspot minimum.

3. SUMMARY

This Technical Publication updates the previous study regarding anticipating cycle 24 minimum and its consequences.[1] Since the last study was completed, it is now confirmed that cycle 23, the present ongoing sunspot cycle, is a cycle of longer than average period. Through December 2007, cycle 23 has persisted for 140 mo from its 12-mma minimum occurrence date of May 1996. For the most reliably determined sunspot cycles 12–22, longer than average period cycles (12–14 and 20) have a 90-percent prediction interval for a period equal to about 139.0±6.9 mo, suggesting only a 5-percent probability that minimum amplitude for cycle 24 will occur after about July 2008. In December 2007, *R* measured 5.0, a value below the median (5.3) and well within the range of previously observed *Rm* values (1.5–12.3).

Also, since the last study was completed, high-latitude new cycle spots have been reported in January, April, and May 2008. This is important because high-latitude new cycle spots have always heralded the start of the new cycle. Because both the weighted mean latitude of all spot groups and the highest latitude spot groups have values that now are increasing with time, having had apparent minima in May/June 2007, sunspot minimum for cycle 24 is believed to be very near. Supporting this is the rapid growth in the number of spotless days, having a monthly maximum, so far, of 28 days in October 2007 and a 12-mma of 18.1 in December 2007, the highest value since cycle 19's *SM* (21.4). The highest value in the modern era is 26.2 (cycle 15). The first spotless day during the decline of cycle 23 occurred in January 2004. To date (through June 2008), there have been 357 spotless days, spanning 53 mo. Previously, we reported that based on extrapolation of inferred fits, the number of spotless days for cycle 24 is not expected to exceed about 560 over about 62 mo (only a 5-percent probability of occurrence), with the last spotless day occurring at least 10 mo after sunspot minimum. It is apparent that minimum amplitude for cycle 24 is extremely close (probably sometime between December 2007 and mid 2008). Presuming minimum amplitude about March 2008 for cycle 24 as presumed by the NOAA Solar Cycle Prediction Panel,[8] it is expected that cycle 24's last spotless day will occur after about January 2009, with sunspot maximum following the last spotless day by about 20–42 mo, indicating sunspot maximum for cycle 24 sometime in 2011–2012. (Note added in proof: Twenty-nine spotless days each were reported in July and August 2008, resulting in 12-mma values of *S* increasing to 19.3 in January 2008 and 21.0 in February 2008.)

Values of the 12-mma of *R*, *G*, *A*, *L*, and *H* presently are close to below median values, while that of *S* is above median value (*S* varies inversely with the other parameters near sunspot minimum). Hence, it is inferred that the parameters are at or very near their minimum values for cycle 24 (at or near maximum value for *S*). From their last occurrences of minimum value (through December 2007), the parametric minimum-to-minimum periods (maximum-to-maximum period for *SM*) measure about 137–140 mo, dependent upon the specific parameter, with all parameters having periods longer than their medians (119–128 mo). Of the parameters, the maximum-to-maximum period for *SM* has the smallest standard deviation (=7.7 mo). Hence, the 90-percent prediction interval for maximum-to-maximum period for *SM* is 128.5±13.9 mo, inferring only a 5-percent chance that cycle 24's maximum-to-maximum period for *SM* will exceed about 142 mo. Thus far, the elapsed time in months from its last SM occurrence (July 1996) measures about 137 mo, inferring that its next SM occurrence (for cycle 24) should come on or before May 2008. Ten of 12 previous cycles have had Rm within 2 mo of SM occurrence, so Rm for cycle 24 probably should be expected within 2 mo of May 2008, corresponding to the interval March–July 2008 (provided May 2008 is $E(SM)$ for cycle 24).

Because parametric minimum values (maximum values for S) are destined to be below median (above median for S) for cycle 24, unless cycle 24 turns out to be a statistical outlier, its RM should be expected to be below median value (about 115) based on the 2×2 contingency tables, or below about 160 based on the modified fits of RM versus parametric minimum values (the upper limits of the 90-percent prediction intervals). Based on the modified fit of RM versus SM, one expects RM for cycle 24 to be below about 132. Of course, if cycle 24 turns out to be a statistical outlier (as is cycle 21), then only real-time monitoring of the progression of the solar cycle using curve fitting techniques (after about 2 years into the cycle) will provide the best estimate for cycle 24's maximum amplitude. It is noted, however, that if in the course of the rise of cycle 24 L exceeds 24 deg, then it is expected that $RM>131$, and if H exceeds 38 deg, then $RM>127$ should be expected. Similarly, if G and A exceed 10 and 2,000 millionths of a solar hemisphere, then it is expected that $RM>117$ and >118, respectively. Close monitoring of the 12-mma values of the parameters will provide continuous estimation of RM. (The NOAA Solar Cycle Prediction Panel[8] has a low, $RM=90\pm10$, and high, $RM=140\pm20$, prediction. Geophysical precursor methods are supportive of the higher prediction).[21–23]

Two-cycle moving averages of the parametric values (minimum and maximum values, as well as timing signatures relative to $E(Rm)$ and $E(RM)$ and the behavior of R in the vicinity of cycle minimum, when $R\leq15$) display apparent long-term trends and patterns that are most intriguing. For example, both minimum and maximum values of R, G, and H, and to a lesser extent A and L, suggest long-term growth from about cycle 14 through cycles 21/22. Similarly, SM has shown continued long-term decay from about cycle 14 through cycles 21/22. Does this presage decreasing values in the future for R, G, and H, and increasing value for S?

Based on a comparison of 2007 12-mma parametric values against superposed epoch analysis curves, minimums in the sum of the deviations are found, such that $E(Rm)$ for cycle 24 should be occurring about anytime between February and September 2008. New cycle spot groups are not expected to become dominant ($G(H)/G\geq0.5$) until after cycle 24's minimum amplitude occurrence (i.e., the minimum value of the 12-mma of R).

Cycle 23's last occurrence of $R\geq15$ was September 2006 and some 15 mo have now elapsed (through December 2007) with R remaining below 15. The cumulative elapsed time that R remains below about 15 is expected to be about 28 mo. Because the median is about 9.5 mo from $E(Rm)$ to $R\geq15$, it is expected that $E(Rm)$ for cycle 24 will be about May 2008.

REFERENCES

1. Wilson, R.M.; and Hathaway, D.H.: "Anticipating Cycle 24 Minimum and Its Consequences," *NASA/TP—2007–215134*, Marshall Space Flight Center, AL, November 2007 (available at <http://trs.nis.nasa.gov/archive/00000768/>).

2. Wilson, R.M.; Hathaway, D.H.; and Reichmann, E.J.: "On the Behavior of the Sunspot Cycle Near Minimum," *J. Geophys. Res.*, Vol. 101, p. 19, 967, 1996.

3. Wilson, R.M.; Hathaway, D.H.; and Reichmann, E.J.: "An Estimate for the Size of Cycle 23 Based on Near Minimum Conditions," *J. Geophys. Res.*, Vol. 103, p. 6595, 1998.

4. Harvey, K.L.; and White, O.R.: "What is Solar Minimum?" *J. Geophys. Res.*, Vol. 104, p. 19,759, 1999.

5. Howard, R.: "2. Solar Cycle, Solar Rotation and Large-Scale Circulation," in Illustrated Glossary for Solar and Solar-Terrestrial Physics," eds. A. Bruzek and C.J. Durrant, D.Reidel Publ. Co., Boston, p. 7, 1977.

6. Wilson, R.M.; and Hathaway, D.H.: "On the Relation Between Spotless Days and the Sunspot Cycle," *NASA/TP—2005–213608*, Marshall Space Flight Center, AL, January 2005 (available at <http://trs.nis.nasa.gov/archive/00000695/>).

7. Wilson, R.M.: and Hathaway, D.H.: "On the Relation between Spotless Days and the Sunspot Cycle: A Supplement," *NASA/TP—2006–214601*, Marshall Space Flight Center, AL, August 2006 (available at <http://trs.nis.nasa.gov/archive/00000735/>).

8. <http://www.swpc.noaa.gov/SolarCycle/SC24/index.html>, accessed 2008.

9. <http://sidc.oma.be/index.php3>, accessed 2008.

10. <ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/ > accessed 2008.

11. <http://solarscience.msfc.nasa.gov/greenwch.shtml>, accessed 2008.

12. Wilson, R.M.; and Hathaway, D.H.: "A Comparison of Rome Observatory Sunspot Area and Sunspot Number Determinations with International Measures 1958–1998," *NASA/TP—2005–214191*, Marshall Space Flight Center, AL, November 2005 (available at <http://trs.nis.nasa.gov/archive/00000716/>).

13. Wilson, R.M.; and Hathaway, D.H.: "On the Relation Between Sunspot Area and Sunspot Number," *NASA/TP—2006–214324*, Marshall Space Flight Center, AL, February 2006 (available at <http://trs.nis.nasa.gov/archive/00000724/>).

14. Dabas, R.S.; Sharma, K.; Das, R,M,; et al.: "A Prediction of Solar Cycle 24 Using a Modified Precursor Method," *Solar Phys.*, 2008, in press.

15. Wilson, R.M.; and Hathaway, D.H.: "Using the Modified Precursor Method to Estimate the Size of Cycle 24," *NASA/TP—2008–215467*, Marshall Space Flight Center, AL, July 2008.

16. Wilson, R.M.; Hathaway, D.H.; and Reichmann, E.J.: "On the Importance of Cycle Minimum in Sunspot Cycle Prediction," *NASA/TP—1996–3648*, Marshall Space Flight Center, AL, August 1996 (available at <http://trs.nis.nasa.gov/archive/00000335/>).

17. Hathaway, D.H.; Wilson, R.M.; and Reichmann, E.J.: "The Shape of the Sunspot Cycle," *Solar Phys.*, Vol. 151, p. 177, 1994.

18. Wilson, R.M.; Hathaway, D.H.; and Reichmann, E.J.: "On Determining the Rise, Size, and Duration Classes of a Sunspot Cycle," *NASA/TP—1996–3652*, Marshall Space Flight Center, AL, September 1996 (available at <http://trs.nis.nasa.gov/archive/00000314/>).

19. Hathaway, D.H.; and Wilson, R.M.: "What the Sunspot Record Tells Us about Space Weather," *Solar Phys.*, Vol. 224, p. 5, 2004.

20. Everitt, B.S.: "The Analysis of Contingency Tables," John Wiley and Sons, New York, NY, p. 15, 1977.

21. Dikpati, M.: de Toma, G.; and Gilman; P.A.: "Predicting the Strength of Solar Cycle 24 Using Flux Transport Dynamo-Based Tool," Geophys. Res. Letts., Vol. 33, p. L05102, doi:10.1029/2005GL05221, 2006.

22. Hathaway, D.H.; and Wilson, R,M.: "Geomagnetic Activity Indicates Large Amplitude for Sunspot Cycle 24," Geophys. Res. Letts., Vol. 33, p. 18101, doi:10.1029/2006GL027053, 2006.

23. Wilson, R.M.; and Hathaway, D.H.: "An Examination of Selected Geomagnetic Indices in Relation to the Sunspot Cycle," *NASA/TP—2006–214711*, Marshall Space Flight Center, AL, December 2006 (available at <http://trs.nis.nasa.gov/archive/00000741/>).

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